The University of Reading

Met Office

Numerical Weather Prediction

Fog Forecasting at Very High Resolution with the Met Office Unified Model

Forecasting Research Technical Report No. 444
Joint Centre for Mesoscale Meteorology Report No. 149

Rachel Capon

email: nwp_publications@metoffice.com

©Crown Copyright

Fog Forecasting at Very High Resolution with the Met Office Unified Model

Rachel Capon

Met Office Joint Centre for Mesoscale Meteorology
Meteorology Building University of Reading Reading RG6 6BB

9 June 2004

Abstract

The presence of fog and low cloud in the lower atmosphere can have a critical impact on both airborne and ground based military operations. High quality predictions of fog formation and dissipation, together with the associated changes in visibility, would therefore be of immense operational value in the field.

However, the many physical processes involved in fog formation interact in a complex and highly non-linear fashion. These interactions are not adequately resolved by current operational mesoscale models. The prediction of fog formation in regions of complex topography requires a full three-dimensional numerical weather prediction model run at a horizontal grid resolution of 1km (or better). In general, the use of such high resolution is not yet feasible for operational mesoscale models, but for the weakly forced situations leading to fog, it may be viable over a small, local area (e.g. 30 km x 30 km).

The aim of this project is to configure and demonstrate an improved fog forecast model, based on the Met Office Unified Model, which will run over a small domain at very high resolution. To this end we here establish and report on the performance of the Met Office current 'state-of-the-art' mesoscale model in forecasting fog when run at 4km and 1km horizontal resolution.

Introduction

The lower part of the atmosphere is crucial to the conduct of military operations. In particular, the presence of fog and low cloud can have a major impact on both airborne and ground based operations. High quality predictions of the formation and dissipation of fog and low cloud, together with associated changes to visibility, would therefore be of considerable operational value in the field. For example, the input of accurate high resolution visibility predictions is essential for the calculations of transmittance performed by the Met Office Electro Optical Tactical Decision Aid NEON.

The formation of fog is a complex and highly non-linear interaction between surface and sub-surface processes, atmospheric radiation, atmospheric turbulence and flows induced by local orography. In particular, very shallow 'drainage' flows due to near-surface cooling on slopes can have a dramatic impact on the local distribution of fog. The atmospheric radiation is critically affected by the presence or lack of overlying cloud, a factor which is itself hard to predict exactly. The dissipation of fog and cloud also involves the complex dynamics generated internally by the fog. Hence, it is very difficult to forecast fog accurately.

Current NWP models, including those implemented as Crisis Area Mesoscale Models (CAMMs), can give a broad indication of fog formation and dissipation on scales of a few tens of km, but can provide little detail and remain unreliable especially in areas of complex terrain. Linear flow models have been developed and validated for potential incorporation into the CMetS battlefield support system. These, however, are inherently unable to treat the very stable flows associated with complex terrain in the presence of weak large scale flow. The Site Specific Forecast Model (SSFM), a one dimensional model based on the Unified Model, has been developed as a cheap alternative with this problem in mind, but it, too, is unable to treat complex three dimensional flows.

A full NWP model running at a horizontal resolution of around 1km (or better) may be required to address the three dimensional fog forecasting problem properly. Enhancement of the CAMMs resolution to such a scale is restrained by available computing power and will therefore not be feasible for many years. However, in the weakly forced situations leading to fog formation, the use of small, local area (e.g. 30 km x 30 km), high resolution versions of the UM may be a viable alternative for particularly sensitive locations.

The potential exists to run such models locally on a high-spec PC. Operationally this would be highly advantageous, not least because it would eliminate the need to send high volumes of forecast data over limited bandwidth communications links. Initial and forcing data would however still be required for the locally run model. Using the current model nesting regime entails communication of large volumes of lateral boundary forcing data. An alternative approach would be the development of a homogeneous forcing method from either global model or local radiosonde data. Such initial data would be of significantly lower volume, facilitating its communication at low bandwidth to the theatre of operation.

For the system proposed, aspects of the current model physics, such as the radiation scheme and microphysics, which have a critical impact on fog formation, must also be assessed and optimised. This is necessary to ensure their accuracy and reliability in the near surface layers of the atmosphere, where fog formation occurs, when the model is run at considerably higher horizontal and vertical resolution than at present.

Aim

The long-term objective of the Development of Very High Resolution Models for Fog and Low Cloud Prediction Project is to improve the quality of detailed local atmospheric predictions of fog and low cloud in situations where local effects such as topography and land-use are dominant. Specifically, the project will demonstrate how the Unified Model may be configured to run on a local PC in the field, over a small high resolution domain, using a low volume of data and hence a low bandwidth for the initial forcing.

The first stage of this project is intended to establish and report on the performance of the Met Office current ‘state-of-the-art’ high resolution mesoscale model in forecasting fog. This model will form the basis of the local model to be developed in the following stages of the project. Assessment of the model has

been done using a case study approach.

Model Configuration

For each case, the Met Office Unified Model v5.5 was run in limited area mode at different resolutions by means of the High Resolution Trial Model (HRTM). The HRTM is a research suite developed at JCMM, which consists of three one-way nested limited area models with grid resolutions of 12km, 4km and 1km, together with the standard verification package. The domains covered by each model are shown in Figure 1. The outermost model is the operational mesoscale model, which is run with 38 vertical levels and a timestep of 5 minutes. For the 4km and 1km models the number of vertical levels is doubled to 76. The timesteps used are 1 minute and 30 seconds respectively.

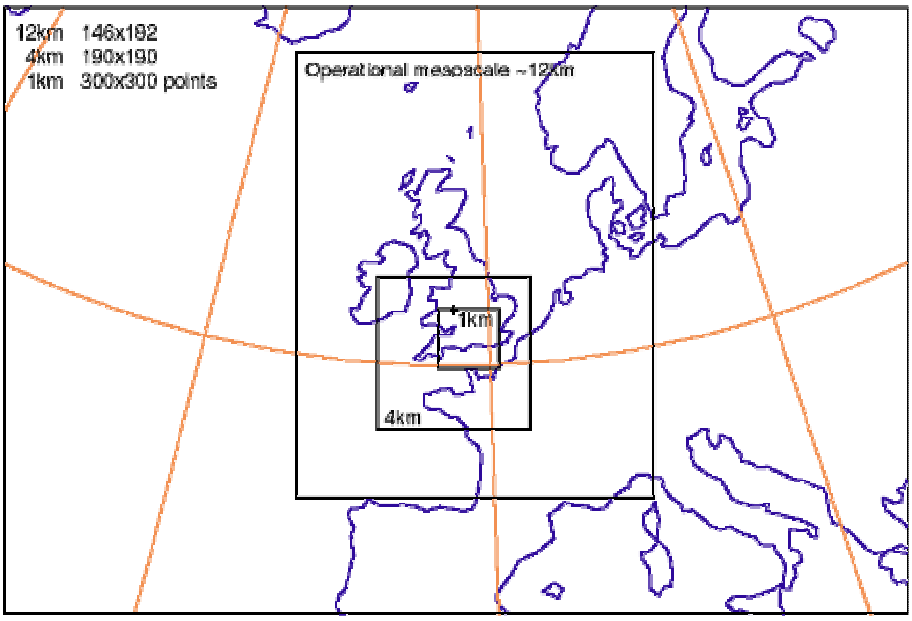


Figure 1 Map showing model domains for 12km (operational mesoscale), 4km and 1km grid resolution models.

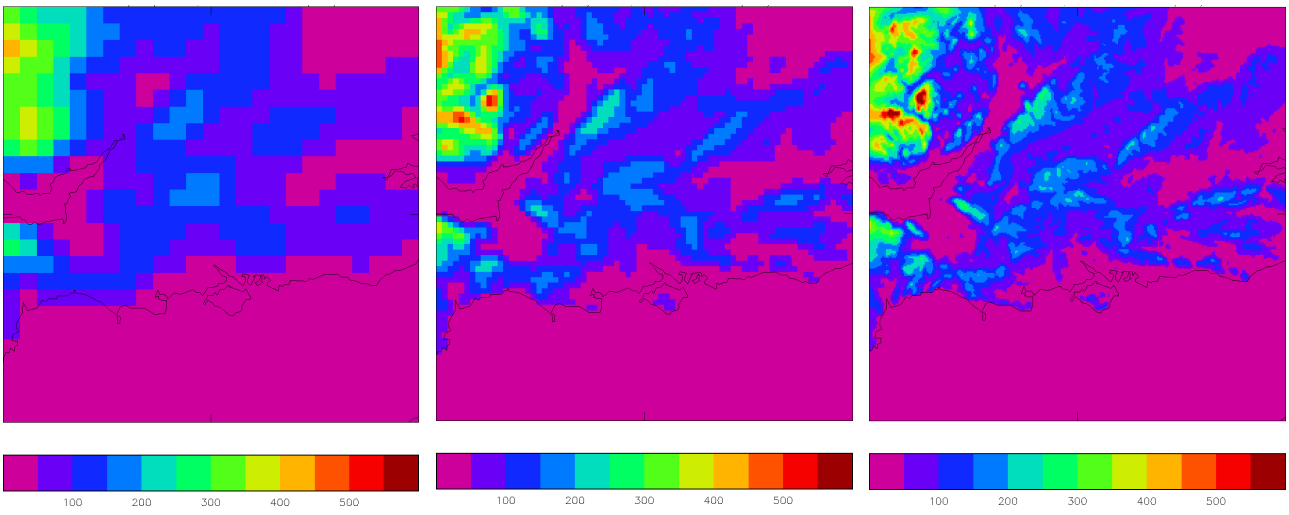


Figure 2 Orography for 12km, 4km and 1km grid resolution models over 1km model domain.

New high resolution ancillaries were created for the land-sea mask, orography and land use for the inner two models. Other ancillary fields were configured from the 12km model start dumps. The source land use dataset has a very high resolution of 100m. However the source orography data was only available at 2km resolution and was smoothed with a Raymond filter in creating the ancillary. Hence the orography field used may be sub-optimal in the case of the 1km resolution model. As orography is an important influence on the formation of radiation fog, this could potentially impair the forecast performance of the 1km model. The orography in each model is shown in Figure 2.

Each case study was run for 24 hours from 18 UTC on the day preceding the main fog event (although for technical reasons the initial data used are actually from 19 UTC). Due to CPU constraints, particularly for running the 1km model, it was actually necessary to run the suite in two consecutive 12 hour blocks.

Verification

Two sources of observations are currently available for fog verification; synoptic observations, which include the visibility at 1.5m and the Nimrod visibility analysis, which incorporates the available satellite data. The model suite included the standard objective verification against surface observations. Subjective verification of the model visibility fields with the surface observations over plotted was also carried out. This considered not only the model visibility at the station locations but also in their vicinity. The pattern and distribution of the fog was considered as well as point values. The network of synoptic stations over the 1km model domain is shown in Figure 3.

Visibility is often considered on a log scale. The order of magnitude of the minimum visibility at any point is as significant as its precise value. Hence, surface visibility observations are not recorded on a continuous linear scale - unlike the model field. Observed visibility below 100m is rounded down to the nearest 10m, from 100m to 5km to the nearest 100m. In the range 6-30km, whole km values are reported. Visibilities above 30km are reported to the nearest 5km.

The observed visibilities (on a log 10 scale) were plotted for each hour as scatter plots against the model visibility at the same point (e.g. Figure 23). (Both the nearest model point and an interpolation from the surrounding grid points were used. In practice there was little difference between them.) The fractional areas of the 1km model domain with visibility at or below the threshold values of 200m and 1km were also plotted as a time series for each model, using the Nimrod visibility analysis for comparison (e.g. Figure 8).

Note that there are differences between visibility observations. At some stations visibility observations are still performed manually. In this case all horizontal directions are taken into account when reporting the minimum visibility. At other stations automatic visiometers are used. These measure the visibility over a 2 litre volume and essentially return a value at a point. They cannot take into account horizontal inhomogeneities in the visibility, which would be apparent to a manual observer. However if the minimum visibility is less than the numerical grid length, it is probably legitimate to consider visibility as a point value.

In addition to the observational uncertainty, some model error is to be expected when just point values are considered. The model height at a station point is often quite different to the actual station height, especially at the coarser model resolutions. This height discrepancy is of the order of 50m for some stations, which is greater than the height of the third model level in the 76 vertical level set. Even in the 1km model, there are height discrepancies of 35m at a few stations. As the development of radiation fog is critically dependent on height this may lead to errors in the diagnosed visibility and fog amount at those station points.

Any verification is subject to sampling error. There are only approximately 50 synoptic observing stations within the 1km domain, compared to a model dataset of ca. 100 grid points for the 12km model or 90 000 grid points for the 1km model. Furthermore the observed visibility may vary on a spatial scale smaller than the grid scale, especially when low visibility occurs during fog events.

The Nimrod visibility analysis is computed via several complex algorithms. The initial analyses of visibility, temperature and dew point are produced from a combination of synoptic observations and satellite imagery. The satellite imagery is used to create a mask which defines fog or low cloud regions where the IR temperature is greater than -15°C. The fog regions are then analysed independently of the other regions.

The purely observational initial analyses are merged with fields from the T+1 mesoscale model forecast to produce the final Nimrod visibility analysis.

There are known errors in the Nimrod visibility analysis. For example, in one of the cases considered, 21 Feb 2003, there are visibility observations of less than 1km from at least one of the stations on Salisbury Plain every hour during the period 05-09 UTC. Yet the Nimrod analysis gives a visibility of 3-4km at these points. Not until 10 UTC does the visibility drop below 2km in the Nimrod analysis. Later investigation by the Nimrod team revealed that some of the observations were not available to the Nimrod system in time. Another known source of error in the Nimrod visibility analysis is the failure to distinguish between fog and clear sky regions from the satellite data and hence diagnosing a fog area as a clear sky region. This error occurs mostly at night when visible satellite imagery is not available.

Currently it is not clear whether the Nimrod analysis provides a more accurate description of the fog than any of the forecast models. As it already contains input from the mesoscale model, it cannot be considered as completely independent for verification purposes.

Improved satellite fog products are expected to be available from Meteosat Second Generation in the near future. These should be immensely useful for verification purposes.

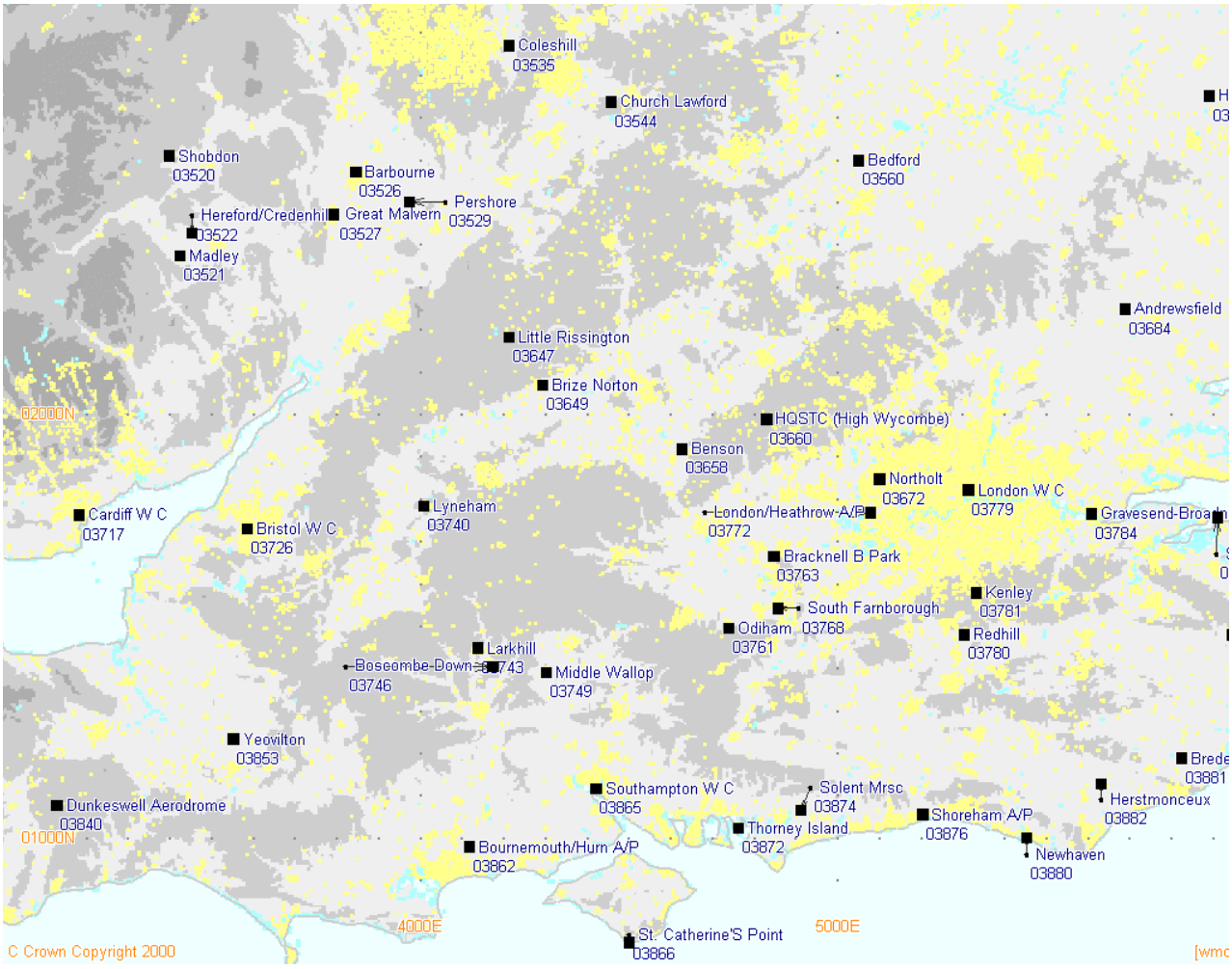


Figure 3 Synoptic station network as at February 2000. Most of the 1km model domain is shown, except the very western edge and the area over the English Channel. Some stations closed during 2003. Charlwood (51.15°N, 0.233°W) is not shown, but is close to Gatwick.

Case Studies

21 February 2003

The synoptic situation was dominated by an anticyclone centred over Sweden. The slack pressure gradient resulted in very light winds of less than 5 knots during the night. By 05 UTC the visibility had fallen to less than 1km at some sites on Salisbury Plain and in Berkshire and Hampshire. In the morning there was quite widespread fog over southern and eastern England. Visibilities of 100m or less were reported at several sites in southern England between 07 UTC and 10 UTC, although by 09 UTC the fog had slightly dissipated in some areas. The dissipation continued rapidly from 10 UTC. By 13 UTC the observed visibilities had increased to values greater than 2km throughout the domain.

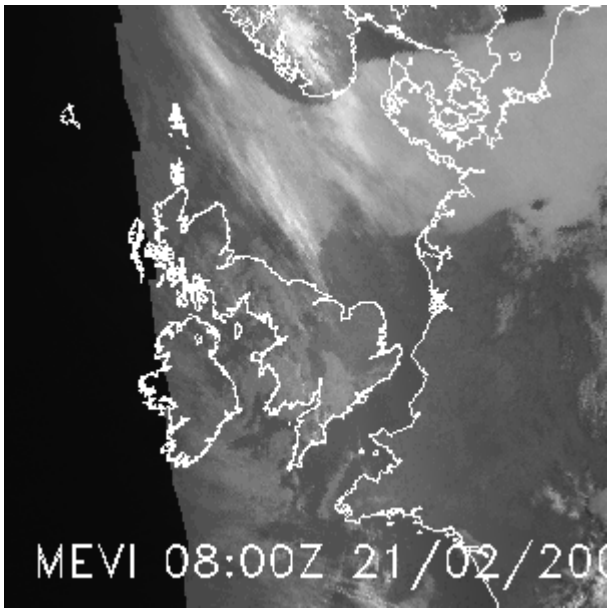


Figure 4 Visible image at 08 UTC 21 Feb 2003 from Meteosat, showing fog over southern England.

MODEL RESULTS

The standard objective verification for the visibility, taken over the 1km domain, shows slightly larger errors in the 12km model during the T+7 to T+14 forecast period (Figure 5). The 12km model has smaller mean and RMS errors in screen temperature for the first 15 hours of the forecast, but later on the 1km and 4km models are more accurate. The mean error shows that the 1km and 4km models are 0.5-1.0 degrees warmer than the 12km model throughout the forecast (Figure 6). The errors in the relative humidity at station height are slightly larger in the 12km model run for the second half of the 24 hour forecast period (Figure 7).

Both the 1km and 4km models have patches of visibility less than 1km in Wales and along the Welsh border from the start of the run. These patches develop and extend throughout the night to give widespread thick fog in this region which reaches its maximum extent by 08 UTC on 21 Feb 2003. In the 12km model the first incidence of visibility below 1km in the area occurs at 0 UTC on 21 Feb 2003. The fog is never as extensive as in the higher resolution models although again the maximum extent is reached by 08 UTC on 21 Feb. The first specific observation of visibility below 2km in this region is at 07 UTC on 21 Feb.

The higher resolution models also have areas of low visibility in Devon from 22 UTC on 20 Feb. (Low visibility first appears in this region much later in the 12km model). There are some corresponding observations from Liscombe, on the edge of Exmoor. However as this is right on the edge of the 1km domain, we will not consider it further.

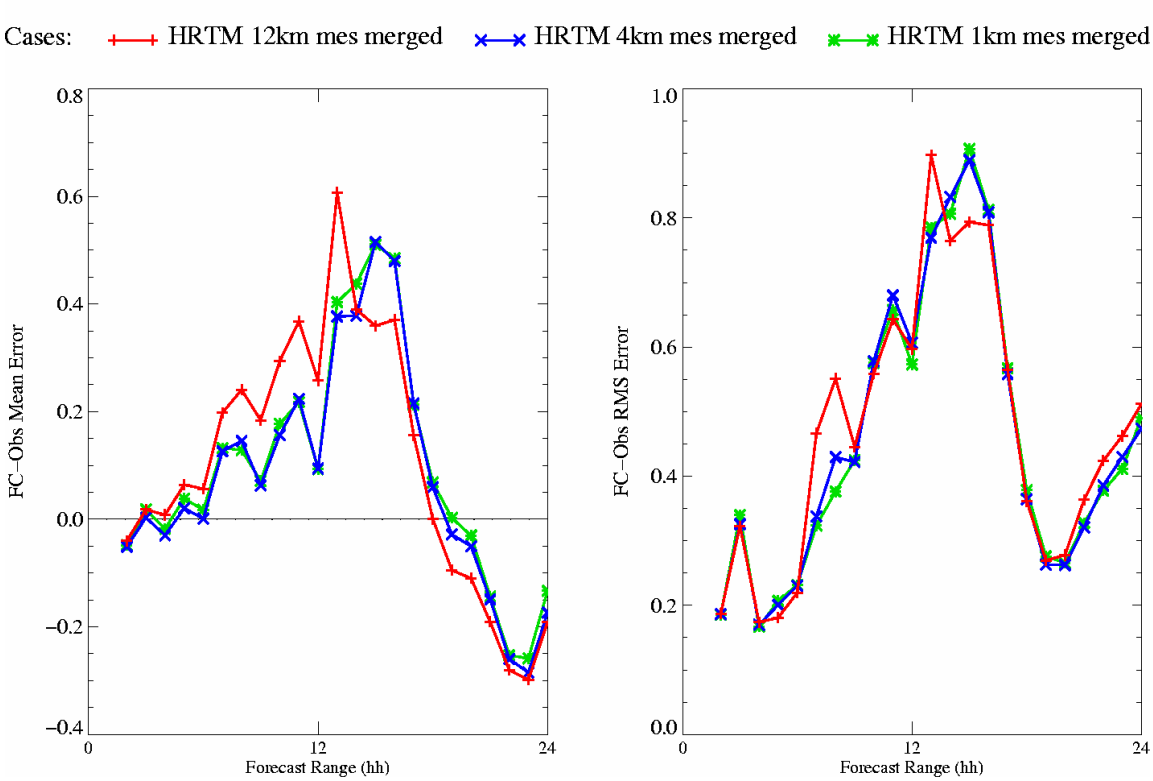


Figure 5 Verification against surface observations over 1km domain of log 10 visibility, forecast from 18 UTC 20 Feb 2003.

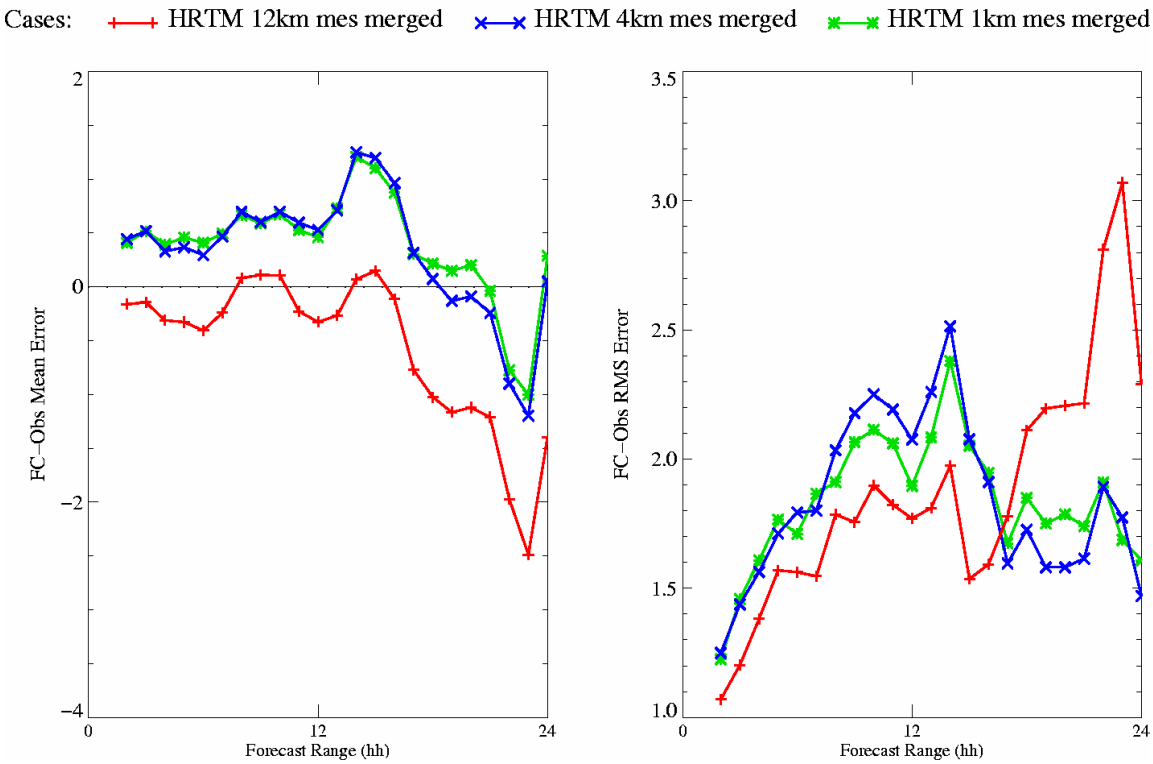


Figure 6 Verification against surface observations over 1km domain of screen temperature, forecast from 18 UTC 20 Feb 2003.

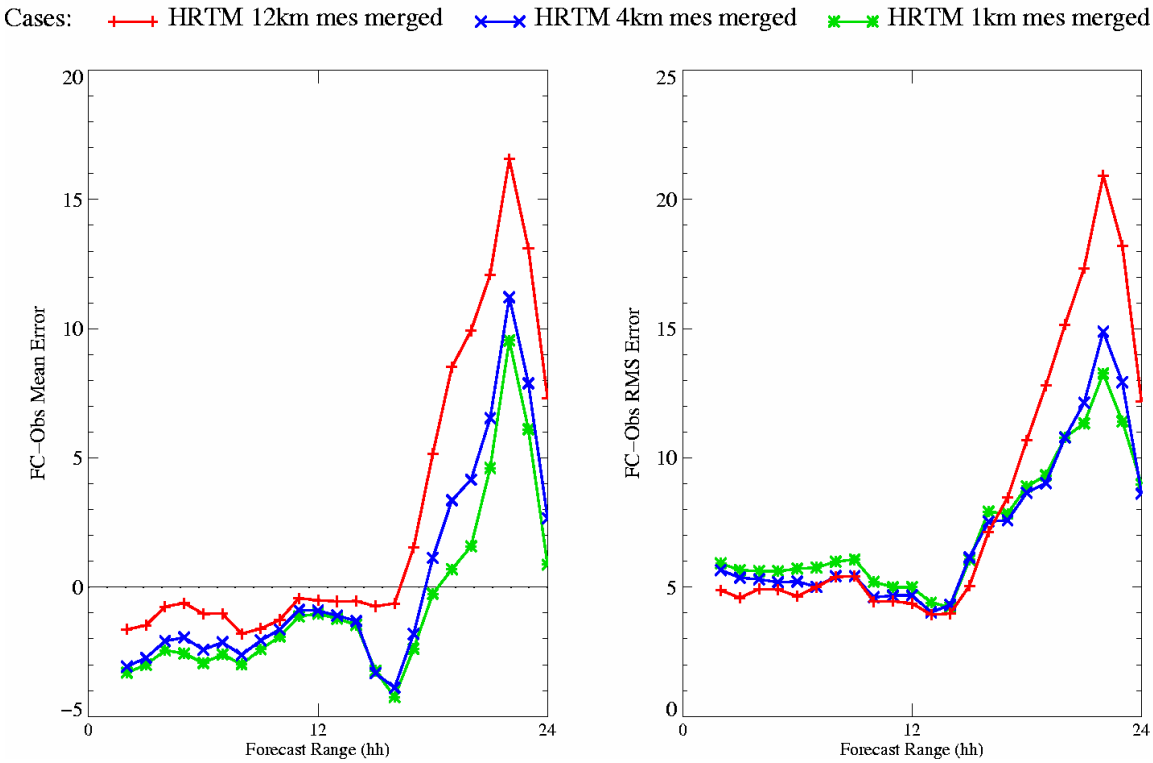


Figure 7 Verification against surface observations over 1km domain of relative humidity (%) at station height, forecast from 18 UTC 20 Feb 2003.

At 03-04 UTC on 21 Feb, small patches of visibility less than 1km or less than 2km appear in southern England in the 1km and 4km models respectively. At the same time, there are some observations of visibilities below 2km on Salisbury Plain and at other locations in southern England, although these are not coincident with the low visibility areas in the models.

By 05 UTC, more coherent areas of low visibility are developing in both the 1km and 4km models (Figure 9). These are the southern Dorset/Salisbury area and West Sussex/Surrey – both of which have minimum visibilities of 200m or below in the 1km model - and over London extending west along the Thames Valley, where there are minimum visibilities of approximately 700m in the 1km model. Low visibility observations at the same time are, in Dorset/Salisbury, 700m on Salisbury Plain (2 sites), 100m at Bournemouth Airport; 500m at Farnborough near the Surrey border and 400m at Bracknell. By contrast, the 12km model has low visibilities (below 2km and down to 300m) only in the Dorset/Salisbury area (Figure 9). In all the models, the fog at this time is mainly at lower elevations, although it does extend over some terrain above 100m in Dorset and the southern part of Salisbury Plain.

During the period 06–07 UTC, the fog is spreading in the 1km and 4km models, both from the areas already noted and in Avon-Wiltshire-South Oxfordshire. Meanwhile in the 12km model, the fog in the Dorset/Salisbury region spreads and the minimum visibility reduces further to below 200m.

By 08 UTC, the fog has reached its maximum extent in all the models. There is now hill fog covering Salisbury Plain and the Mendips. The fog has also spread, with the synoptic flow, to cover the south-east facing slopes of the Cotswolds and Chilterns (Figure 10). This is also the time at which the lowest visibility observations occurred in the domain, with 10 stations reporting visibilities of 200m or below. In the 12km model, it is only at 08 UTC that visibilities below 2km appear in W Sussex, the Thames Valley and Oxfordshire. However the model visibility in these areas does not fall significantly below 1km. As already noted, the higher resolution models have both earlier and denser fog formation in these regions. They are also in greater agreement with the observations.

Between 08 UTC and 09 UTC, rapid clearing of the fog has already commenced in the 1km and 4km models. Over Salisbury Plain the fog dissipates, but in Somerset it may just have lifted into low cloud.

Noticeable clearing of the fog in the 12km model is first apparent at 10 UTC. However several sites are still reporting low visibilities, in some cases down to 100m, at 09 UTC and 10 UTC on the morning of 21 Feb. At 09 UTC, many of these observations are still nearly captured by the models, but at 10 UTC only those in the west of the domain are. This gives the impression that the fog is dissipating too quickly, especially in the higher resolution models. Alternatively, the observations may indicate that some small localized fog patches, which are not captured by the model, remain after much of the fog has dispersed.

Patches of low visibility remain in the Welsh border region until 11-12 UTC in all three models. Interestingly, an area of low visibility uncorroborated by observations lingers over London until midday and even longer in the 1km model.

Figure 8 shows the fractional area (of the 1km domain) with visibility less than or equal to the threshold values of 200m and 1000m for each of the models. The plots demonstrate that both fog formation and fog dissipation occur 1-2 hours earlier in the higher resolution models than in the 12km model. Furthermore, the maximum area with visibility below 200m is a third greater in the 1km and 4km models compared to the 12km model, indicating that denser fog is formed by the higher resolution models, at least in some regions, as was already noted from the subjective verification.

This figure also includes visibilities from the Nimrod analysis and clearly shows that the Nimrod analysis diagnosed much less fog than any of the models during the 04-10 UTC period on 21 Feb 2003, due to unavailability of some of the surface observations.

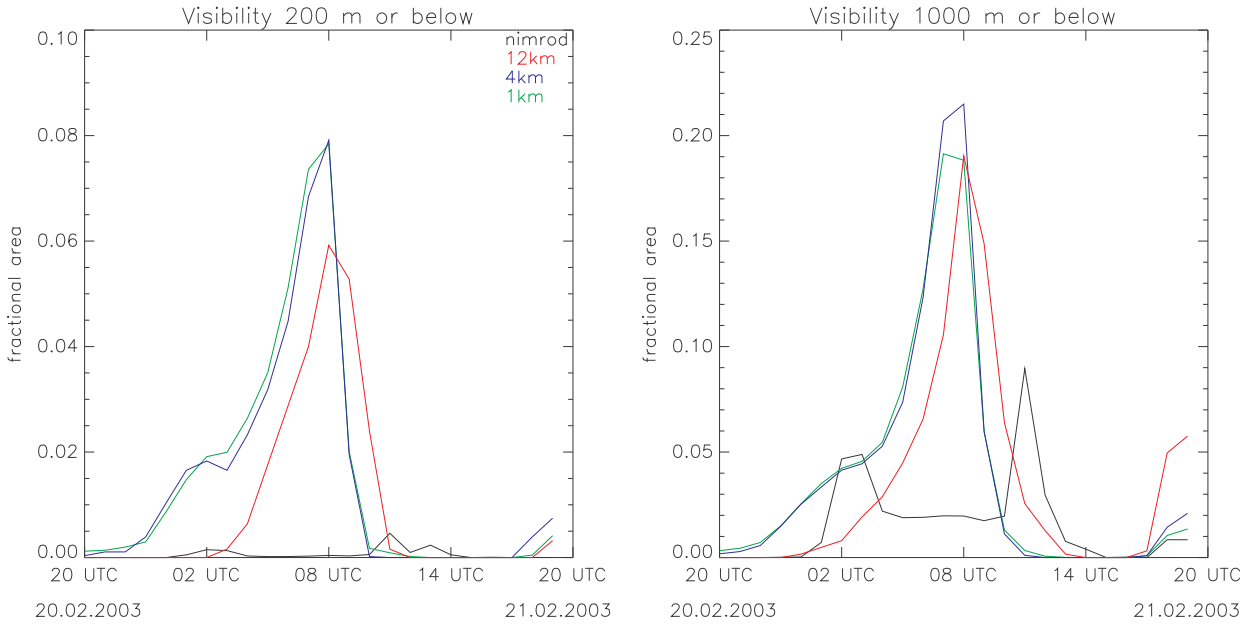


Figure 8 Fractional area of the 1km domain with visibility less than or equal to the threshold values of 200m (left) and 1000m (right) for each model and for the Nimrod visibility analysis. Forecast from 18 UTC 20 Feb 2003.

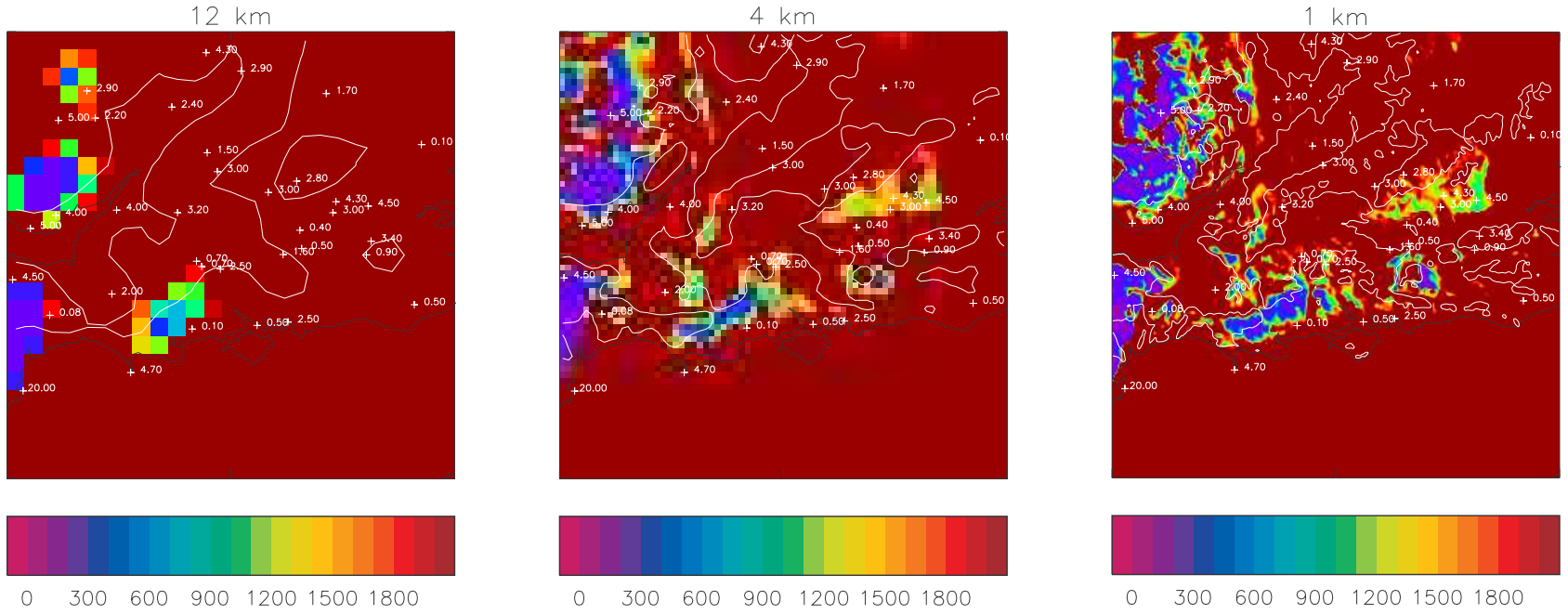


Figure 9 Visibility (m) at 1.5m at 05 UTC 21 Feb 2003 from 18 UTC 20 Feb 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 05 UTC 21 Feb 2003 and the 100 m model orography contour are overlaid. There is noticeable fog development in southern Dorset and the Salisbury area. The 1km and 4km models also indicate fog development in West Sussex and in London and the Thames Valley.

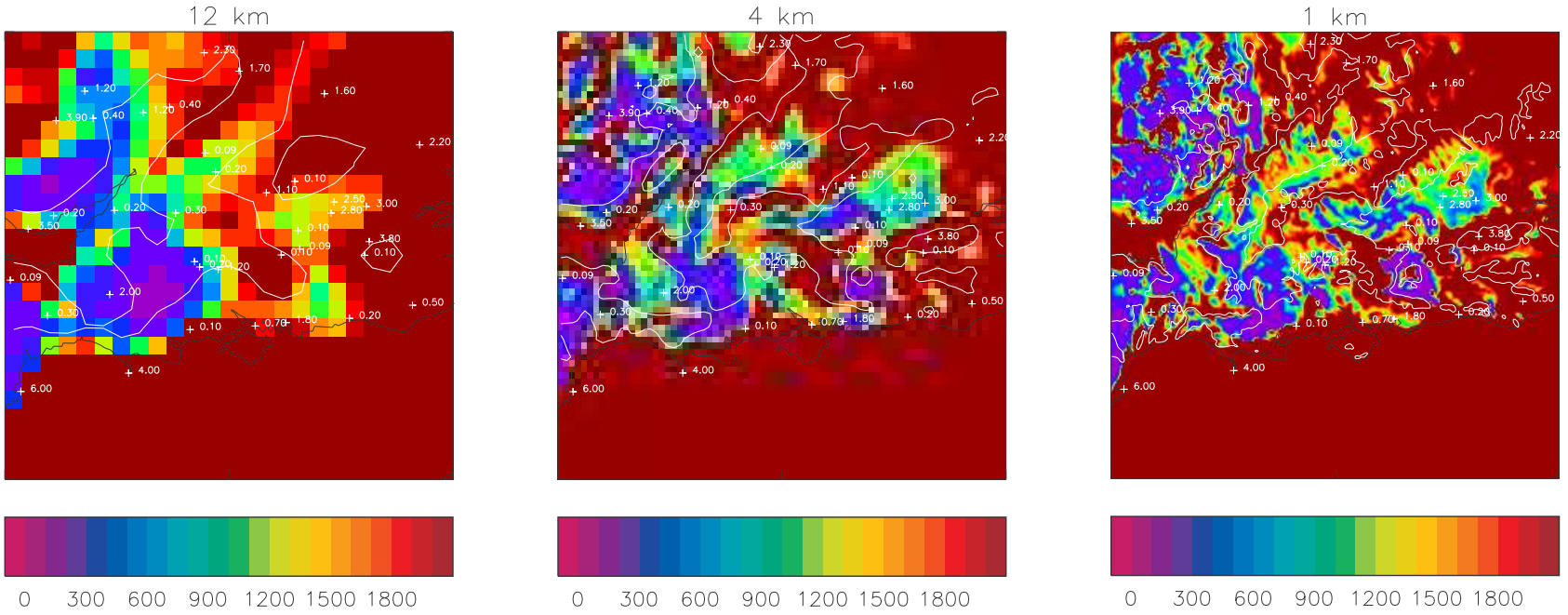


Figure 10 Visibility (m) at 1.5m at 08 UTC 21 Feb 2003 from 18 UTC 20 Feb 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 08 UTC 21 Feb 2003 and 100 m model orography contour are overlaid. Extensive fog now covers Salisbury Plain and the Mendips. There is also fog in the Cotswolds, Chilterns and Thames Valley and West Sussex/Surrey, but the fog in these regions is much denser in the 1km and 4km models than in the 12km model.

7 November 2003

The synoptic situation was strongly influenced by an anticyclone, with central pressure of 1047hPa, centred over the Baltic States. There were very light easterly winds during the night and minimum temperatures of between 3°C and 9°C. Widespread mist and fog patches were forming by evening on 6 Nov 2003 leading to extensive fog across the UK. This fog cleared during the morning in southern England but lingered into late morning across northern England and the Midlands.

MODEL RESULTS

For visibility, the standard verification demonstrates very little difference between the three models (Figure 11). If anything, the 12km model is slightly better towards the end of the forecast period, but only marginally so. The 12km model has smaller mean and RMS errors in screen temperature and relative humidity at station height up to T+15, but after this the 1km and 4km models are more accurate (Figure 12, Figure 13). The 1km and 4km models again have a screen temperature which is about 0.5 degrees higher than in the 12km model (Figure 12).

In Wales and along the Welsh border, both the 1km and 4km models have extensive low visibility, reaching a minimum of approximately 100m, from the start of the run until 10-11 UTC on 7 Nov 2003, at which time the fog dissipates here. In the 12km model, there is also low visibility in this region. However the initial minimum visibility is only about 1km at 20 UTC on 6 Nov 2003. From 23 UTC the visibility actually increases slightly in the 12km model before decreasing again at 06–08 UTC on 7 Nov 2003, after which time the fog dissipates.

The first corresponding observation of low visibility in the Wales and Welsh border region is at 23 UTC on 6 Nov 2003 at Hereford, when a value of 100m is returned. In fact the observed visibility at Hereford is 100m or less during the entire period 02–08 UTC on 7 Nov 2003.

At 21 UTC there are low visibility observations of 100m, 200m and 80m at Larkhill, South Farnborough and Redhill respectively, which are not reproduced in any of the models. An hour later, at 22 UTC, areas of low visibility begin to develop north of the Thames in Essex in each model. Between 23 UTC and 00 UTC patches of low visibility develop in Sussex/Surrey in the 1km and 4km models. These are located at or close to stations with corresponding observations at Redhill, Charlwood and South Farnborough (Figure 15).

During the period 01–04 UTC, the fog develops and spreads north of London and along the Thames Valley in both the 4km and 1km models. The visibility is reduced to 100-200m in some small areas. North Oxfordshire and Northamptonshire are also affected by the fog (Figure 16). In the 12km model, the visibility reduces in and around London to a minimum of 400m at 03 UTC, but the fog only spreads thinly westward along the Thames Valley somewhat later, from 04 UTC. Also in this model, the visibility in North Oxfordshire only falls to 1.5km at 04 UTC before increasing again.

For each hour between 02 UTC and 07 UTC, there are some stations reporting visibilities of 200m or below and others reporting values of 300m – 1km. None of the models are entirely consistent with the observations, but the higher resolution models perform better than the 12km model. In fact, each of the models produces a fairly bland and relatively uniform fog, with average visibilities in the northern half of the domain of around 1-2km for the 1km and 4km models and 1.5-3km for the 12km model. It is possible that the fog had more local variation in intensity on the ground, which is not fully captured by the models.

The fog in the Thames Valley dissipates in all the models between 08 and 09 UTC. Figure 17shows the situation at 08 UTC on 07 Nov 2003. It takes marginally longer to dissipate the fog in North Oxfordshire in the 4km and 1km models. As is often the case, the model fog dissipates last in Wales. The fog dissipation is illustrated by the plot of cloud liquid water path from the 1km model (Figure 18).

Figure 14 shows the fractional area (of the 1km domain) with visibility less than or equal to the threshold values of 200m and 1000m for each of the models. This confirms that the 1km model produced the most fog for this case and that both the 1km and 4km models produced significantly more fog than the 12km model. However, the most noticeable feature is that, in this case, the Nimrod visibility analysis contains an order of magnitude more fog than even the higher resolution models.

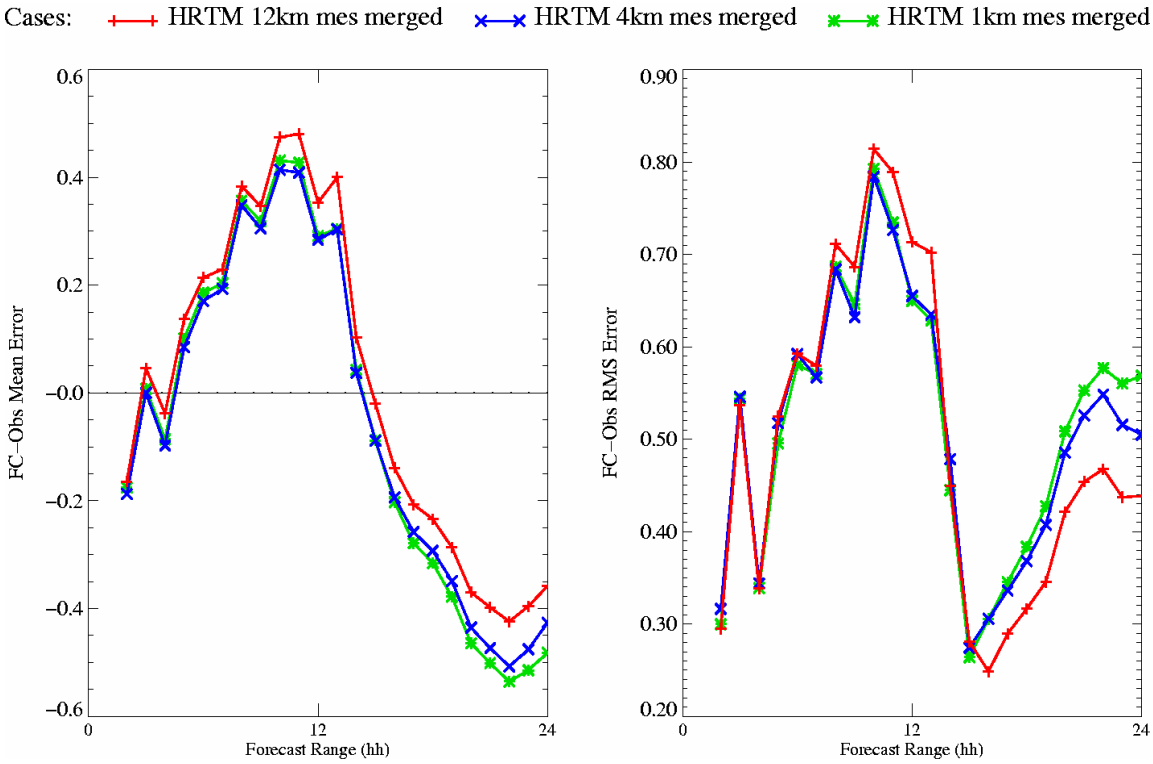


Figure 11 Verification against surface observations over 1km domain of log 10 visibility, forecast from 18 UTC 06 Nov 2003.

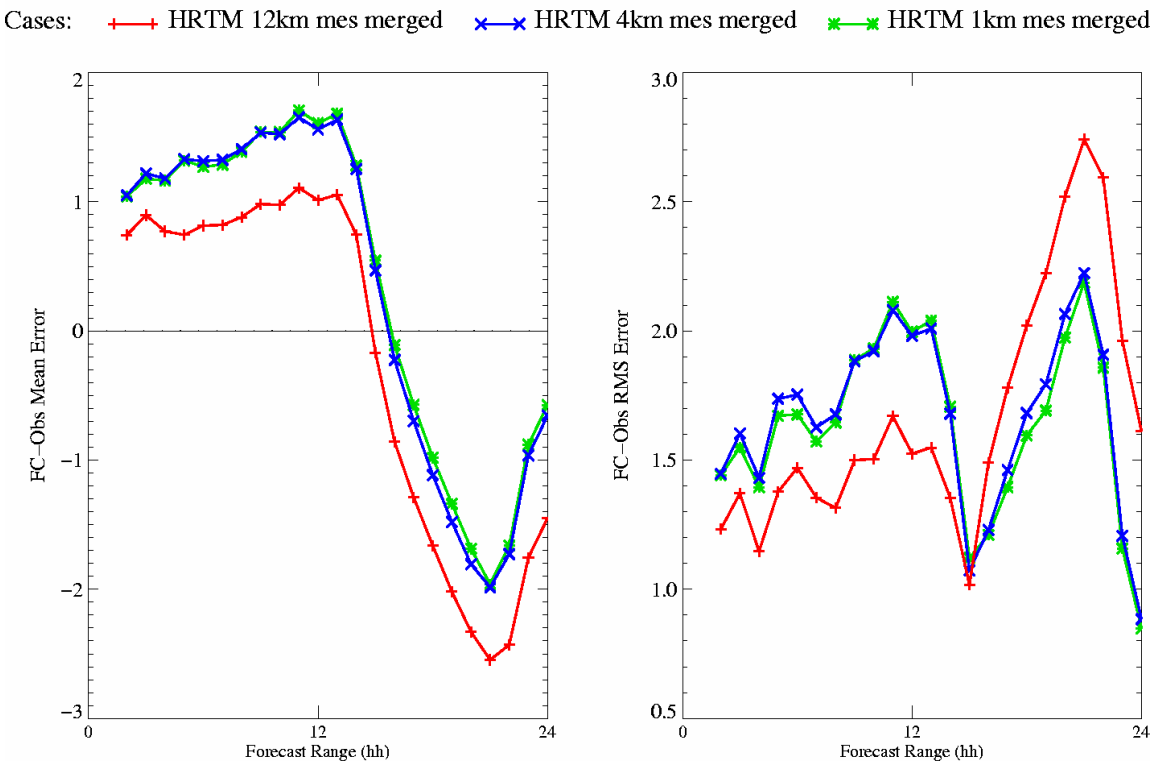


Figure 12 Verification against surface observations over 1km domain of screen temperature, forecast from 18 UTC 06 Nov 2003.

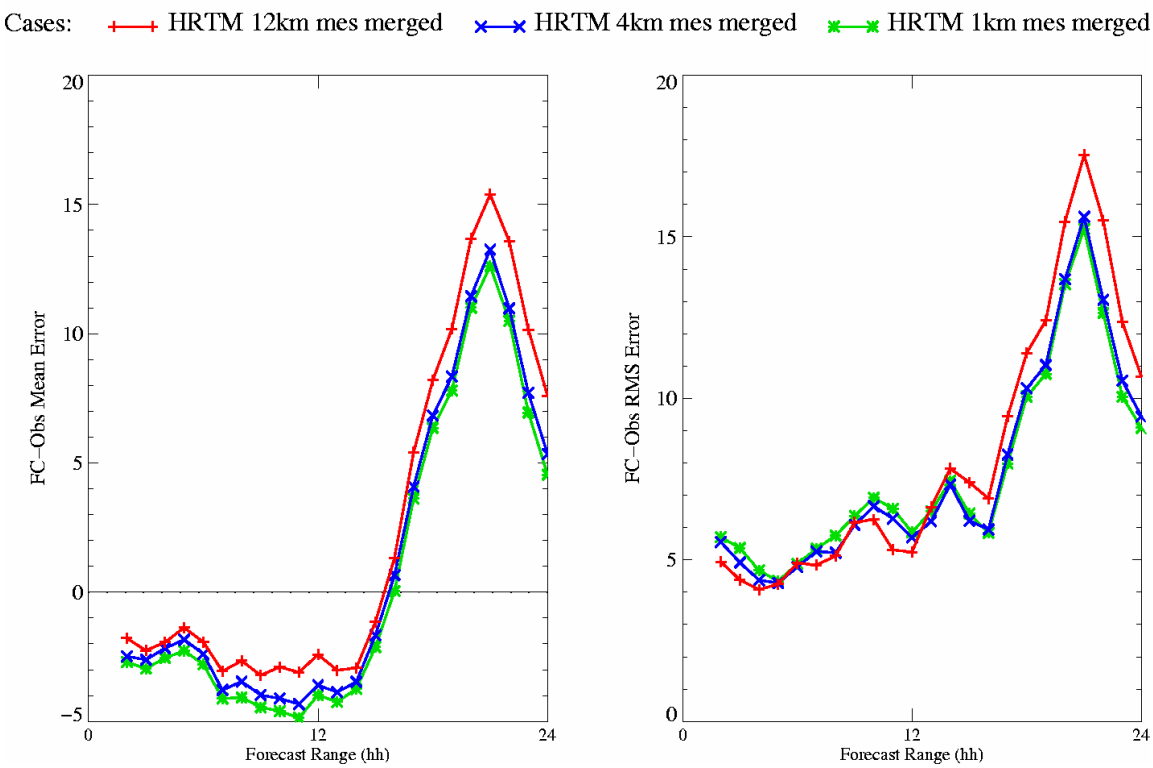


Figure 13 Verification against surface observations over 1km domain of relative humidity (%) at station height, forecast from 18 UTC 06 Nov 2003.

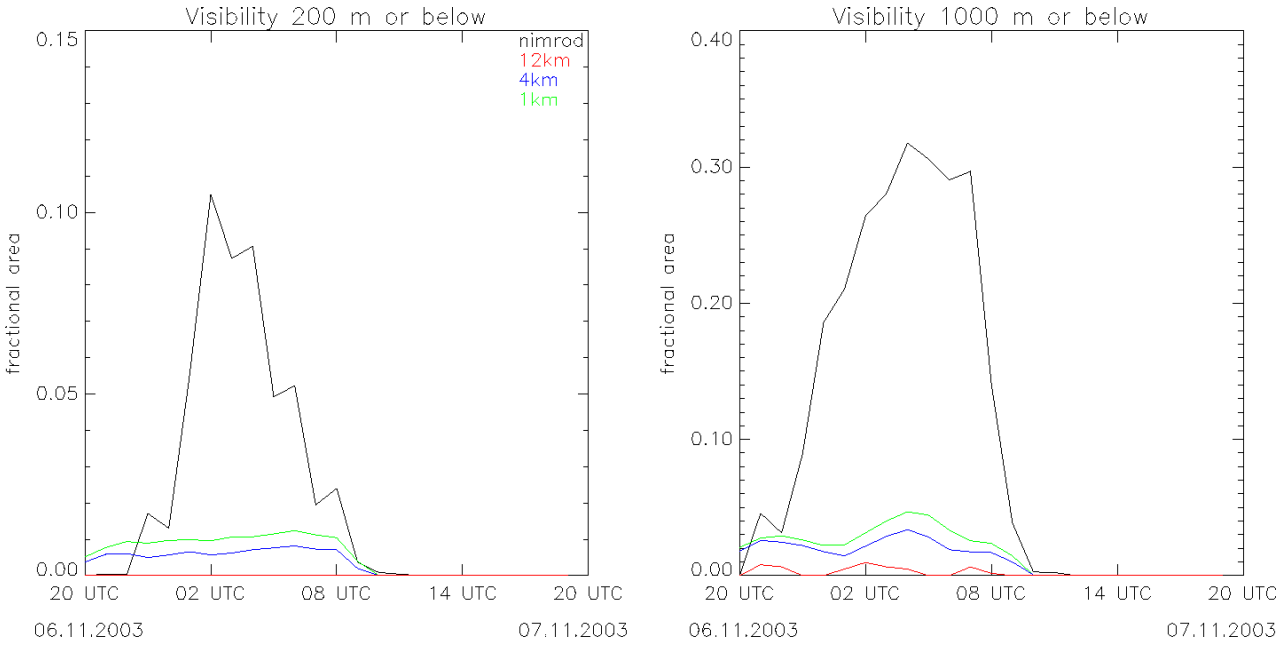


Figure 14 Fractional area of the 1km domain with visibility less than or equal to the threshold values of 200m (left) and 1000m (right) for each model and for the Nimrod visibility analysis. Forecast from 18 UTC 06 Nov 2003.

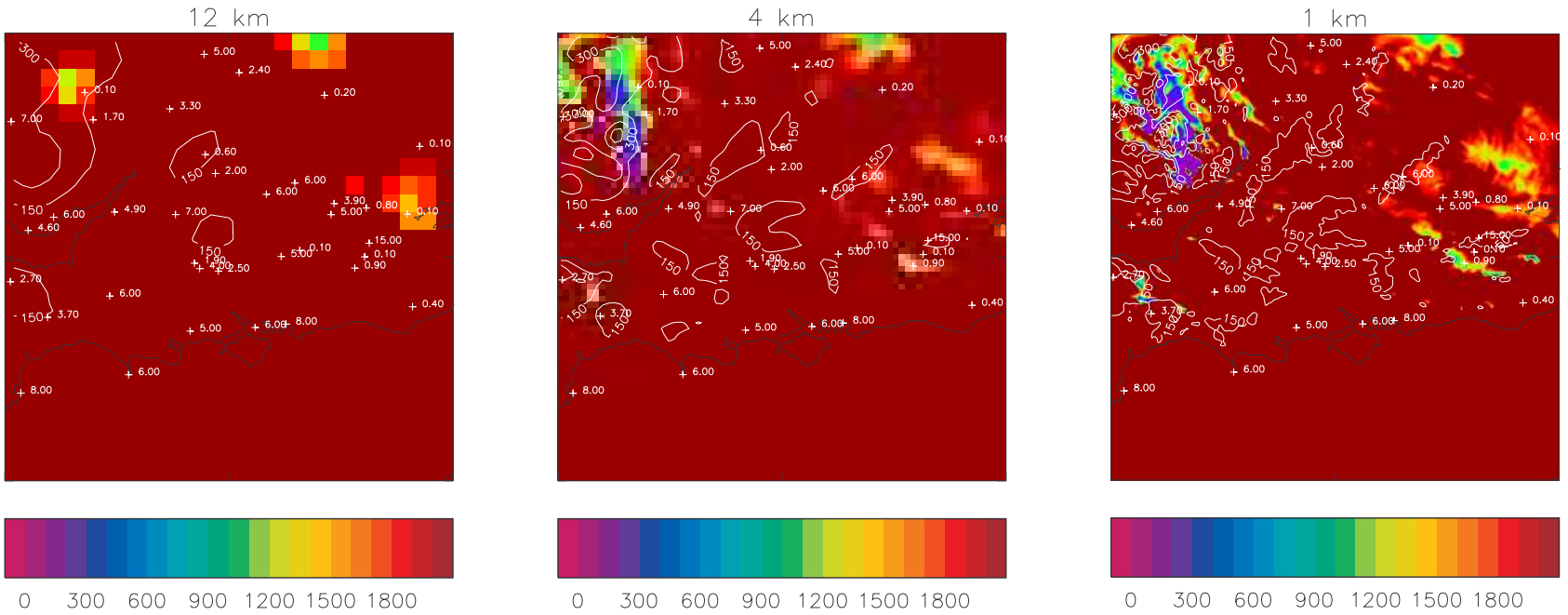


Figure 15 Visibility (m) at 1.5m at 00 UTC 07 Nov 2003 from 18 UTC 06 Nov 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 00 UTC 07 Nov 2003 and model orography contours (at 150m intervals) are overlaid. Low visibility areas are developing in Essex and, in the 1km and 4km models, in Sussex/Surrey. Note the corresponding observed low visibilities at South Farnborough, Charlwood and Redhill.

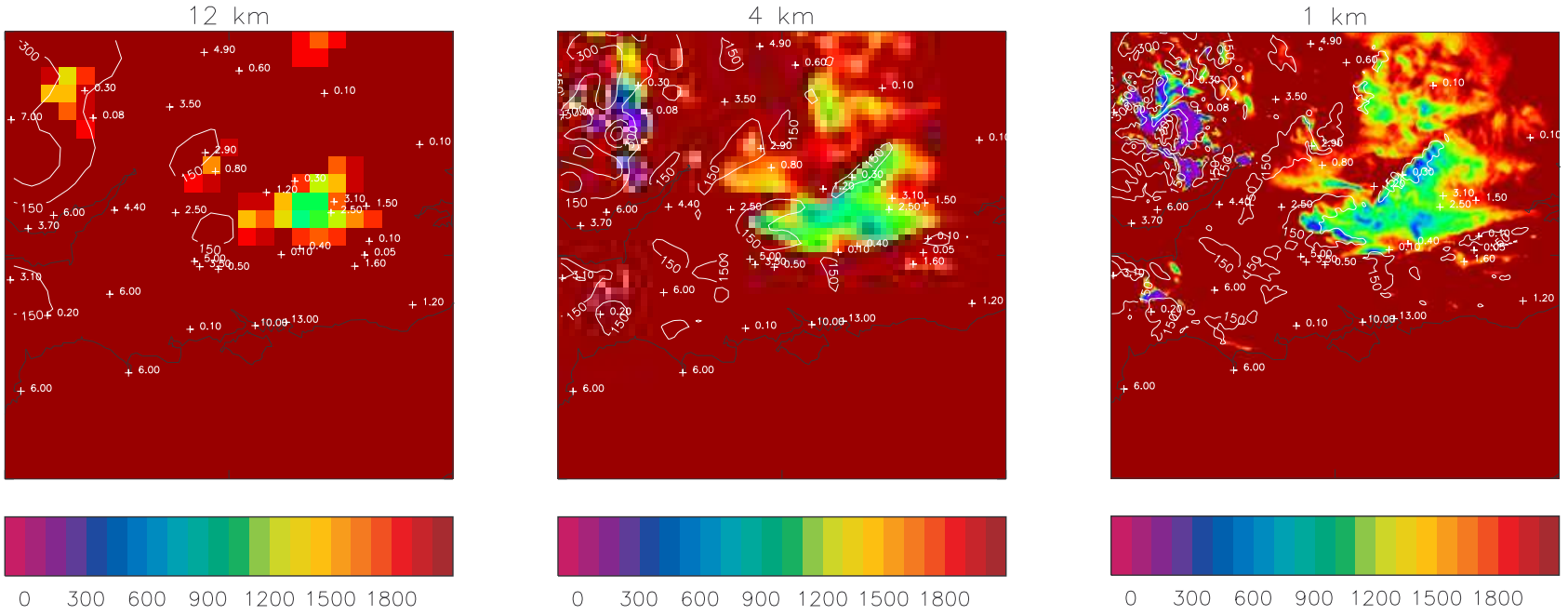


Figure 16 Visibility (m) at 1.5m at 04 UTC 07 Nov 2003 from 18 UTC 06 Nov 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 04 UTC 07 Nov 2003 and model orography contours (at 150m intervals) are overlaid. There is widespread fog in the Thames Valley, Northamptonshire and North Oxfordshire in the 1km and 4km models. The 12km model shows considerably less fog.

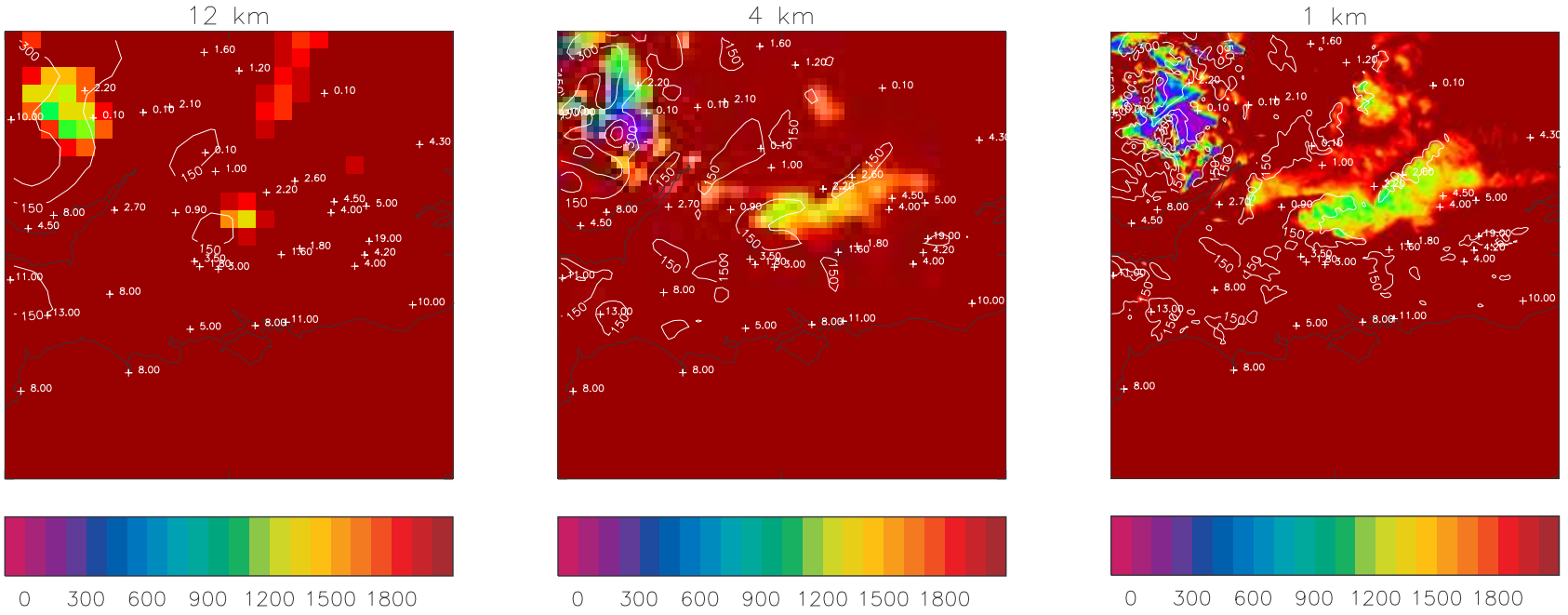


Figure 17 Visibility (m) at 1.5m at 08 UTC 07 Nov 2003 from 18 UTC 06 Nov 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 08 UTC 07 Nov 2003 and model orography contours (at 150m intervals) are overlaid. Fog dissipation is evident in all the models.

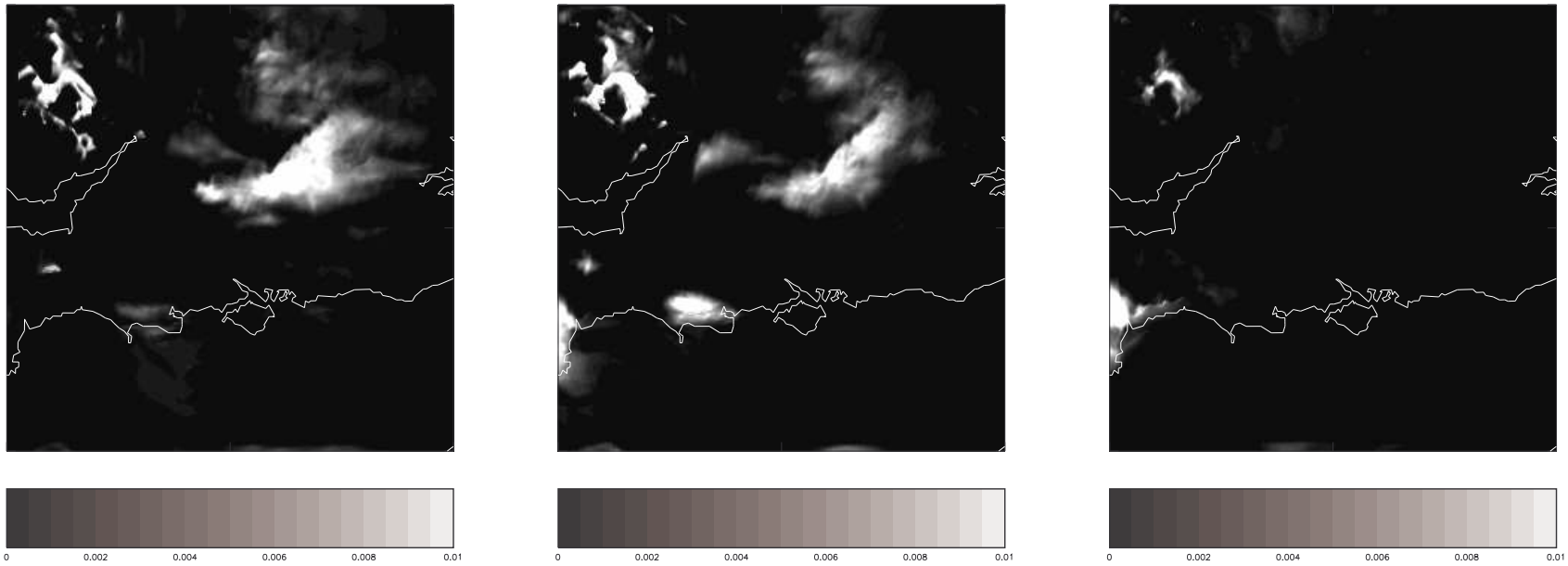


Figure 18 Cloud liquid water path over lowest kilometre of the atmosphere in the 1km model, from 18 UTC 06 Nov 2003 at (left to right) 04 UTC, 07 UTC and 10 UTC 07 Nov 2003.

10 December 2003

This case was a genuine 'pea-souper'. The synoptic pattern was dominated by a high pressure area extending over the UK from Europe. The persistent, dense fog began forming during the evening of 9 Dec 2003. Many sites in England and Wales observed visibilities of 200 or 100m or less between 00 UTC and midday on 10 Dec 2003. Thinning of the fog was observed at some sites during the early afternoon, but in the south-east of England the fog thickened again towards dusk.

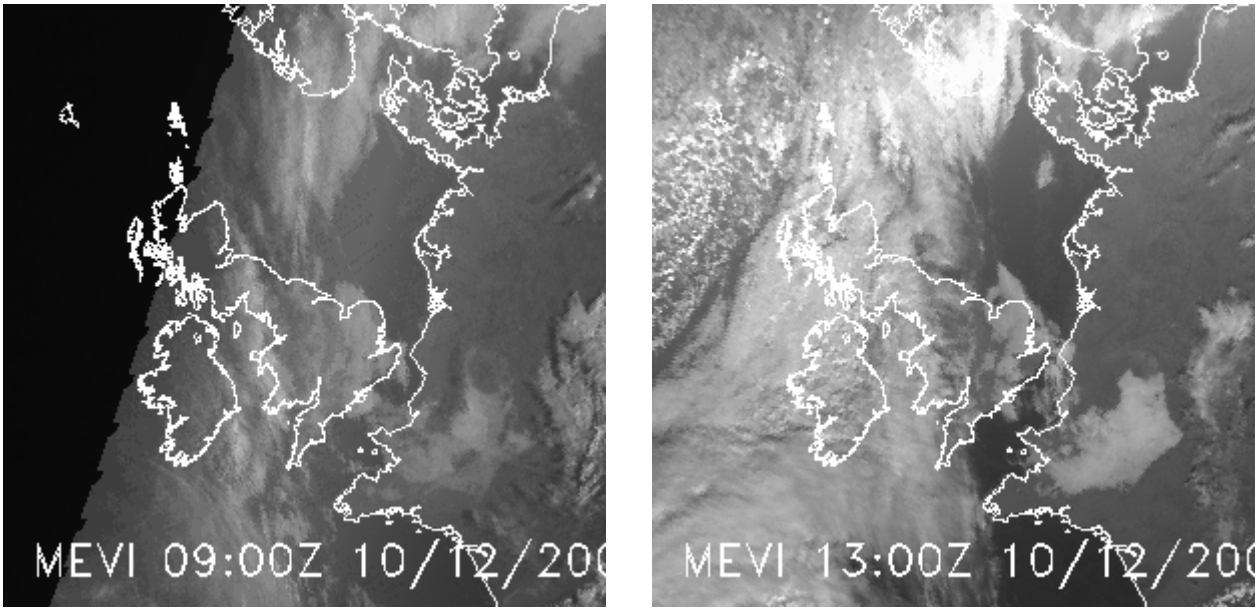


Figure 19 Visible images at 09 UTC (left) and 13 UTC (right) on 10 Dec 2003 from Meteosat, showing widespread fog over England in the morning, which is breaking up in the afternoon.

MODEL RESULTS

In terms of the standard objective verification, all three models show similar errors in (log 10) visibility for the first six hours of the forecast. After this, the RMS error for the 12km model is noticeably larger than for the 4km and 1km models. The 12km model has RMS errors of an order of magnitude, whereas the RMS errors for the 4km and 1km models are approximately 0.6-0.7 orders of magnitude (Figure 20). Again there is a 0.5-1.0 degree bias in the screen temperature in the 1km and 4km models. The mean error in screen temperature is less in the 12km model compared to the other two models up to T+18. However the screen temperature RMS error for the 12km model is only smaller than in the other models up to T+10 (Figure 21). For the relative humidity, up to T+18, the mean error is greatest in the 12km model and least in the 1km model. After this the mean error is least in the 4km model. The RMS errors in relative humidity vary throughout the forecast with none of the models performing consistently better or worse than the others (Figure 22).

At 20 UTC, the 12km model has areas with visibility of 1km or less in low-lying areas, in the Welsh borders, along a line from Bournemouth to London, in North Oxfordshire and in East Anglia (Figure 25). The same areas have lower minimum visibility in both the 4km and 1km models. Over the following hours the fog spreads from these areas and intensifies in each model. The observed visibilities during this period range from below 100m to 5-10km. The models are more consistent with the observations in some areas, such as the Welsh border region and Hampshire, than in others, for example North Oxfordshire.

By 00 UTC in the 1km and 4km models and by 01-02 UTC in 12km model, the visibility falls below 100m throughout most of the domain - with the exception of Kent and Sussex and the tops of hills in Wales and the Cotswolds. In the 1km and 4km models the tops of the Mendips and the Chilterns also remain clear. As might be expected, these hilltops are better defined as the model resolution increases and the contrast in visibility compared to the surrounding valleys is also more apparent (Figure 26).

During the period 03–05 UTC on 10 Dec 2003, the visibility also reduces over the Chilterns in the 1km and 4km models. In addition, the extent of the clearer areas, with visibility above 2km, on the tops of the Cotswolds and Mendips decreases. In the 12km model the fog thickens through the early hours over the Cotswolds giving a maximum visibility of 400m there by 07 UTC. The 12km model also shows some thickening of the fog in Surrey and West Sussex, but this is not confirmed by the observations; the three stations south of London (Kenley, Redhill and Charlwood) all report visibilities above 2km from 04–11 UTC. The situation at 07 UTC on 10 Dec 2003 is illustrated in Figure 27.

Dissipation of the fog over the hilltops commences by 09 UTC in the 12km model and by 10 UTC in the 4km and 1km models. By early afternoon, 13–14 UTC, the fog has significantly cleared in the 4km and 1km models (Figure 28). Examination of the cloud liquid water path from these models confirms that the fog has either dissipated or settled, rather than simply lifted (Figure 29). Just low-lying areas, such as the Thames Valley and parts of Somerset, are still obscured. This is fairly consistent with the observations at the time, which are low (100-300m) for example in West London and at RAF Benson but high (> 10km) at more elevated sites such as Strike Command in High Wycombe and at Little Rissington in Oxfordshire. In the 12km model, the fog clearance is more limited and less consistent with the surface observations. This is illustrated by the scatter plots of model versus observed visibility in Figure 23.

During the late afternoon, from 16-17 UTC, the fog starts to reform in the 12km model. In the 1km and 4km models the re-thickening of the fog commences up to an hour earlier. However it remains clearly confined to low-lying areas. This would concur with the quite high visibilities observed by some of the more elevated stations (High Wycombe, Kenley, Larkhill and Little Rissington) during the 16-18 UTC time period.

The fractional areas of the 1km domain with visibility less than or equal to the threshold values of 200m and 1km for each model are plotted in Figure 24. This shows that dense fog with visibility less than 200m forms 1-2 hours earlier in the higher resolution models. It also illustrates the significant dissipation which occurs during the afternoon of 10 Dec 2003 in the higher resolution models, but not in the 12km model.

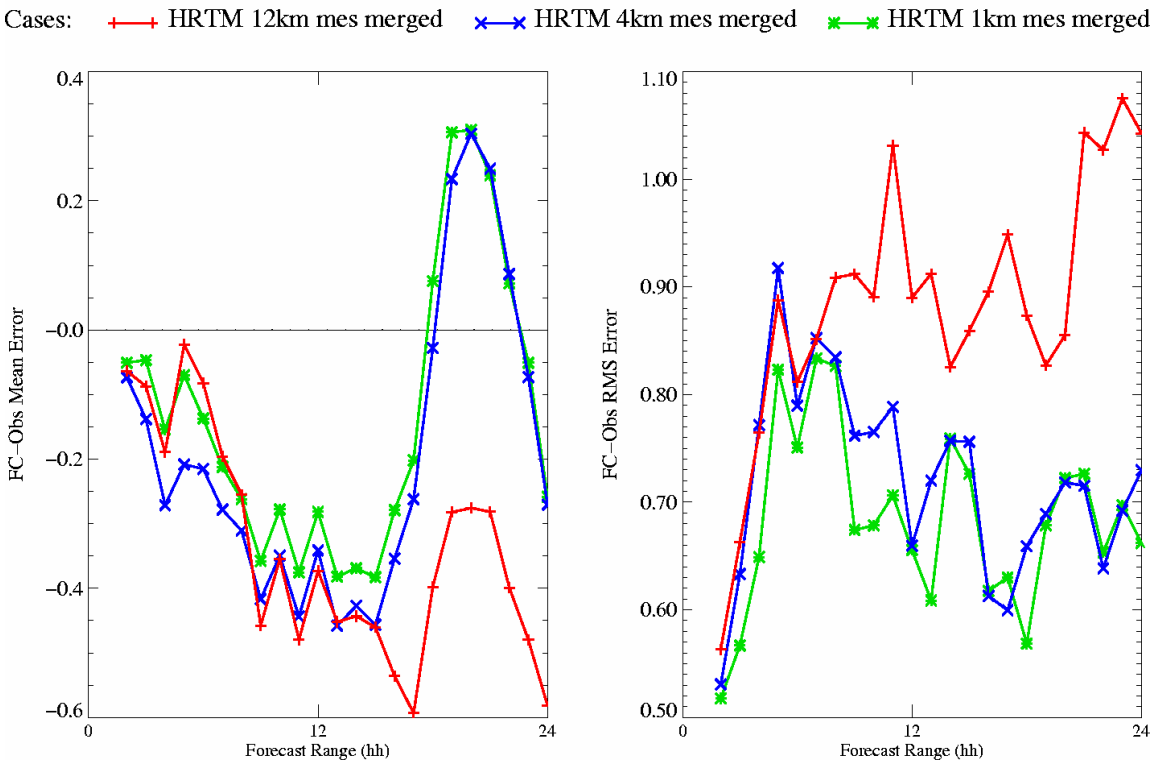


Figure 20 Verification against surface observations over 1km domain of log 10 visibility, forecast from 18 UTC 9 Dec 2003.

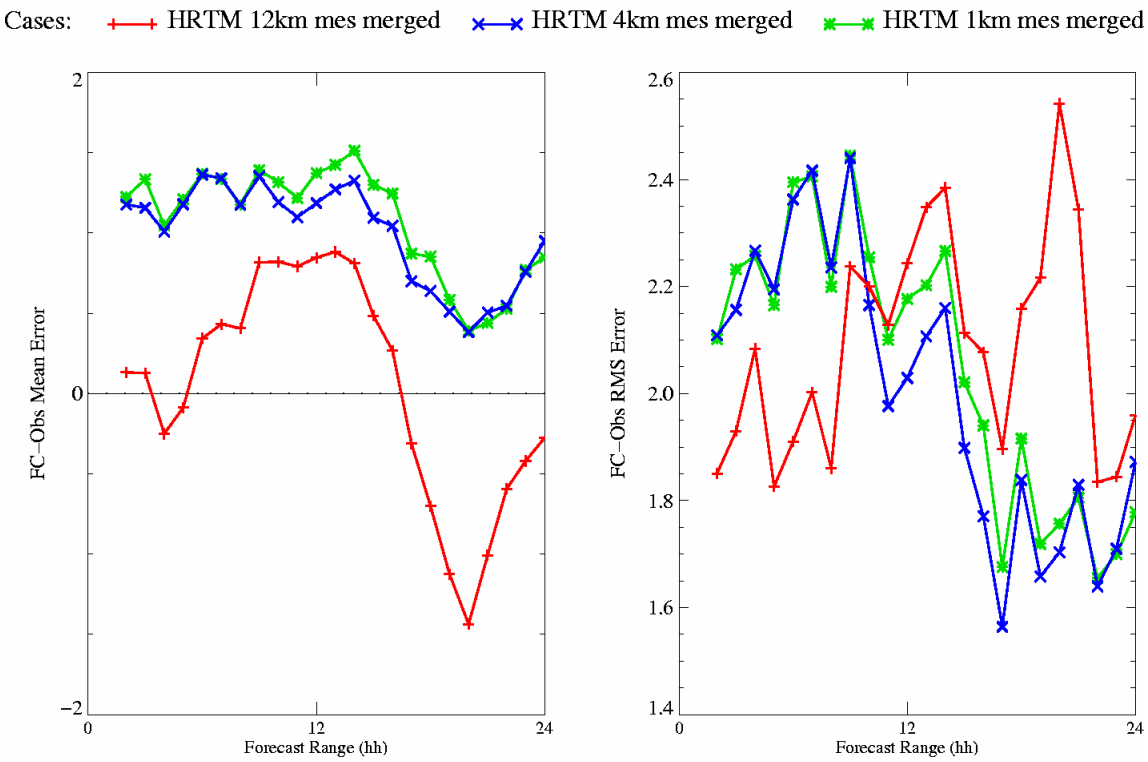


Figure 21 Verification against surface observations over 1km domain of screen temperature, forecast from 18 UTC 09 Dec 2003.

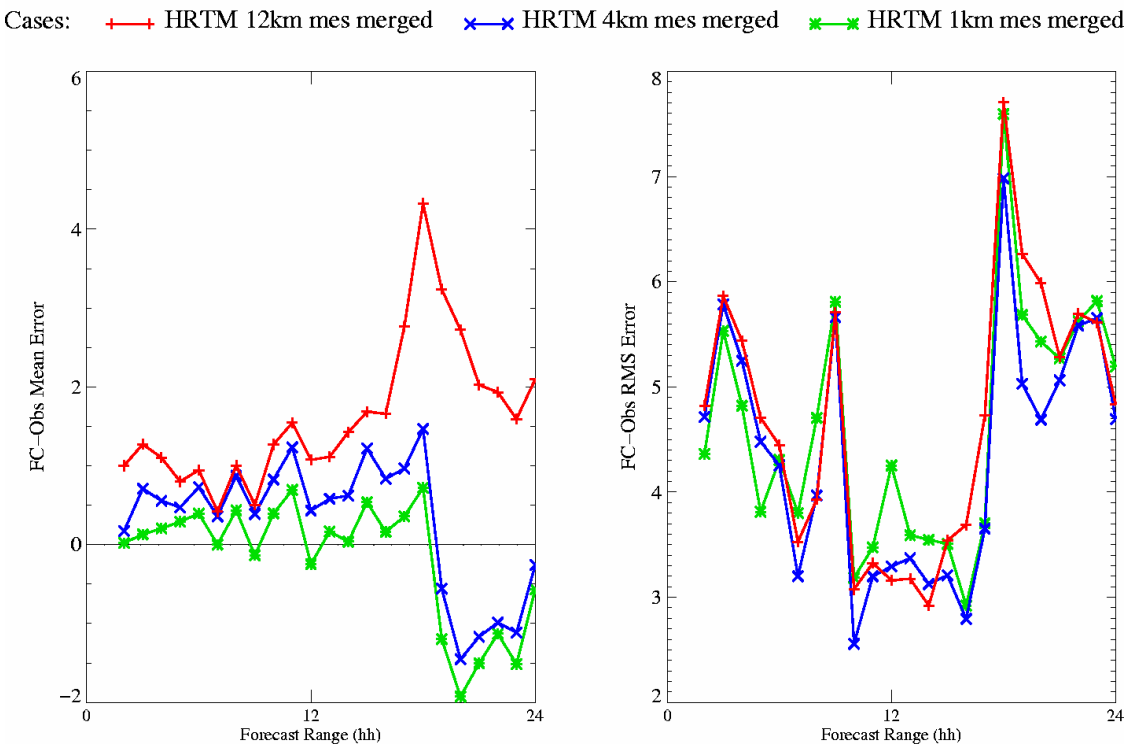


Figure 22 Verification against surface observations over 1km domain of relative humidity (%) at station height, forecast from 18 UTC 09 Dec 2003.

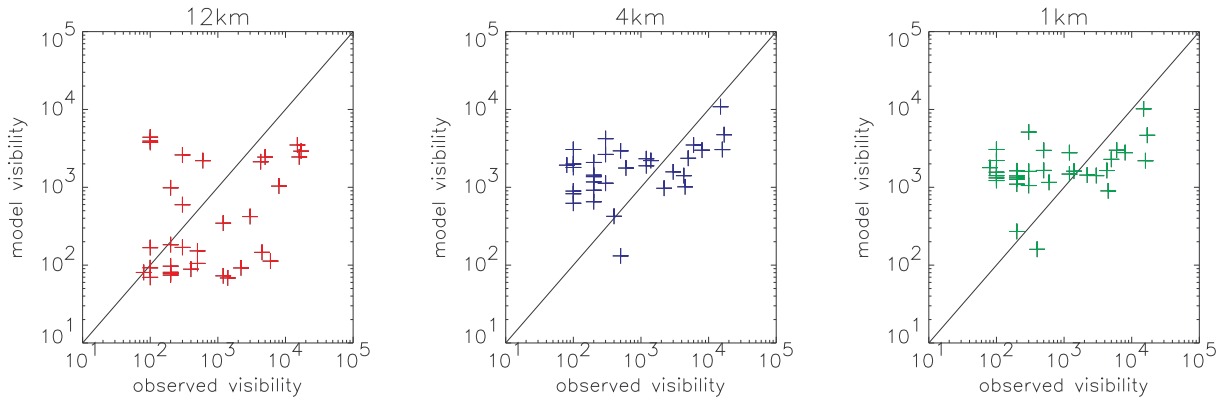


Figure 23 Scatter plots of model visibility versus observed visibility at 1.5m at 14 UTC on 10 Dec 2003 for 12km, 4km and 1km models. Too little fog dissipation has occurred in the 12km model, which is predicting too low values for some visibilities. On the other hand, the 4km and 1km models are predicting too high visibility values at some stations.

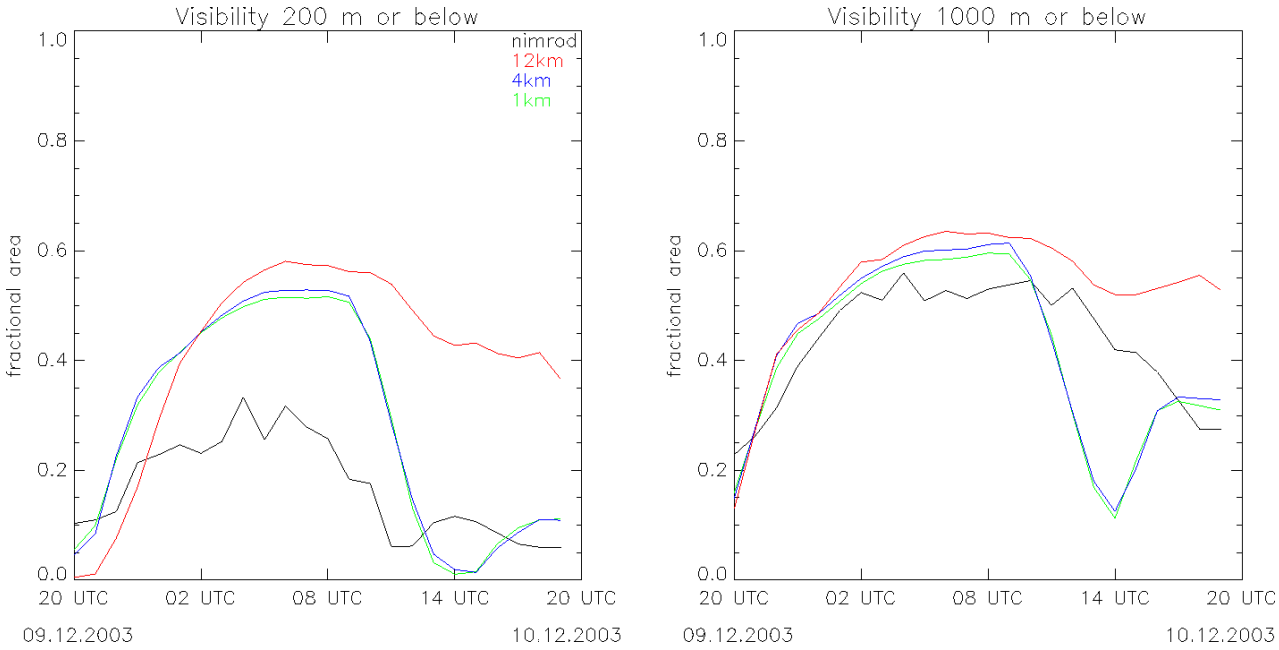


Figure 24 Fractional area of the 1km domain with visibility less than or equal to the threshold values of 200m (left) and 1000m (right) for each model and for the Nimrod visibility analysis. Forecast from 18 UTC 09 Dec 2003.

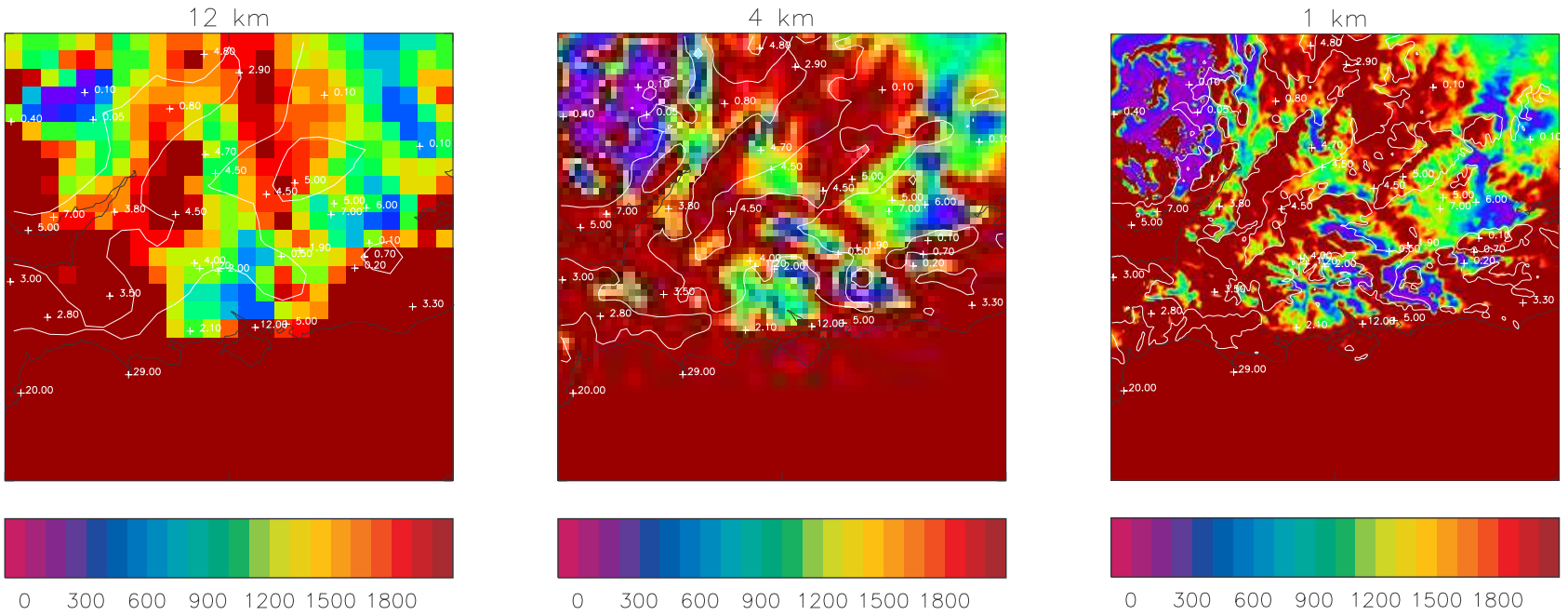


Figure 25 Visibility (m) at 1.5m at 20 UTC 09 Dec 2003 from 18 UTC 09 Dec 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 20 UTC 09 Dec 2003 and 100 m model orography contour are overlaid. There is already fog in low-lying areas.

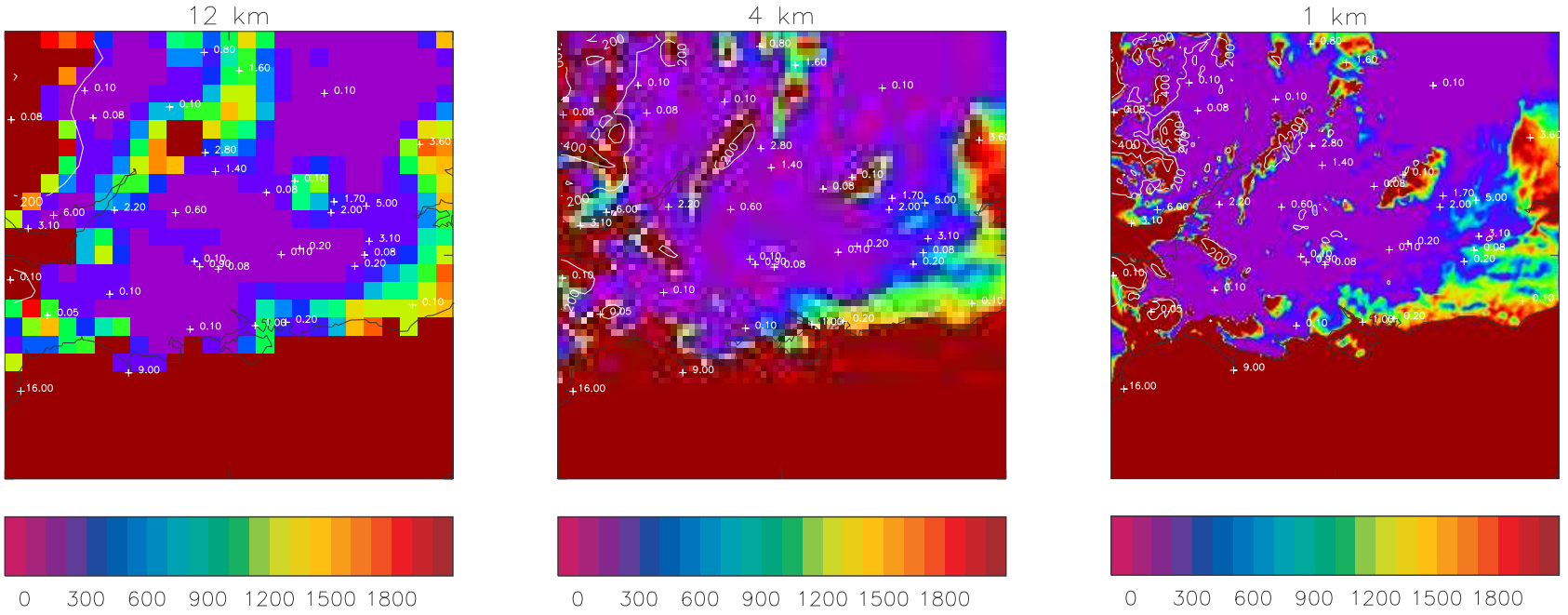
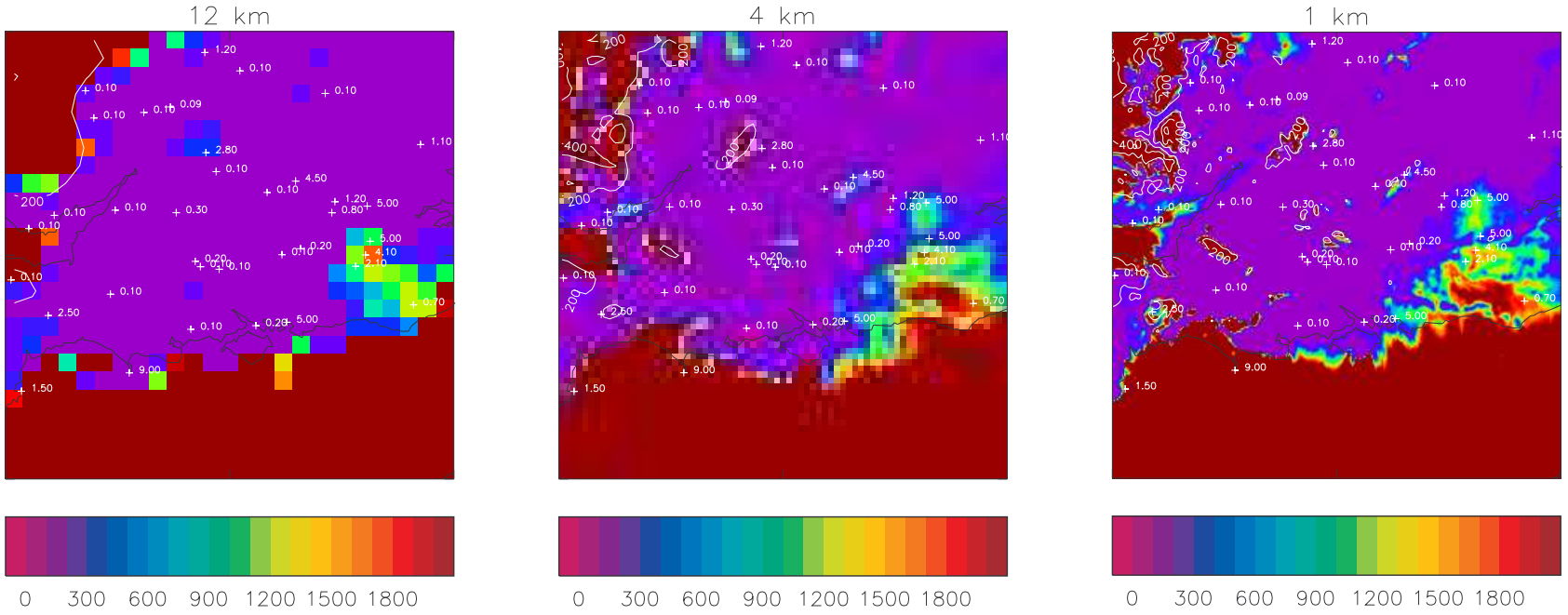


Figure 26 Visibility (m) at 1.5m at 01 UTC 10 Dec 2003 from 18 UTC 09 Dec 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 01 UTC 10 Dec 2003 and model orography contours (at 200m intervals) are overlaid. There is thick fog throughout most of the domain although hill tops remain clear.



.

Figure 27 Visibility (m) at 1.5m at 07 UTC 10 Dec 2003 from 18 UTC 09 Dec 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 07 UTC 10 Dec 2003 and model orography contours (at 200m intervals) are overlaid. The fog has thickened even further. In the 1km and 4km models the peaks of the Cotswolds and Mendips remain clear and the Chilterns are just discernible. Sussex is also relatively clear in the 1km and 4km models, but not in the 12km model.

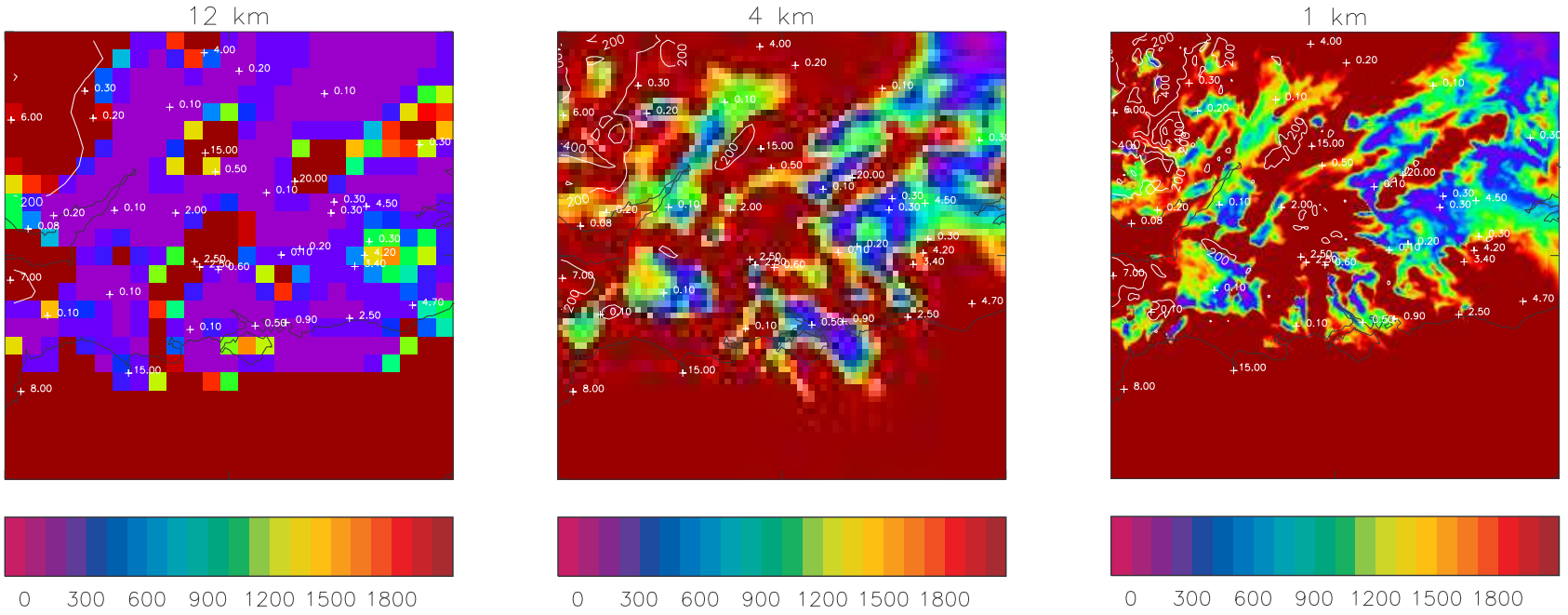


Figure 28 Visibility (m) at 1.5m at 13 UTC 10 Dec 2003 from 18 UTC 09 Dec 2003 for the three models, shown over the 1km domain. Visibility observations (in km) at 13 UTC 10 Dec 2003 and model orography contours (at 200m intervals) are overlaid. The fog has dissipated significantly in the 1km and 4km models, but less in the 12km model.

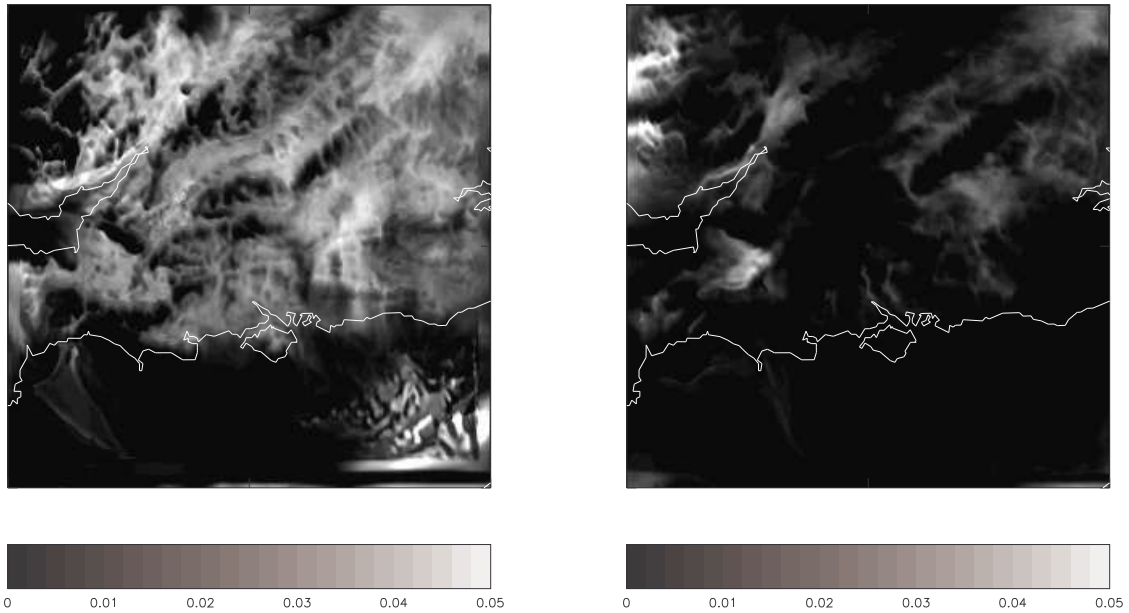


Figure 29 Cloud liquid water path over lowest kilometre of the atmosphere in the 1km model, from 18 UTC 09 Dec 2003 at 07 UTC 10 Dec 2003 (left) and 13 UTC 10 Dec 2003 (right).

Conclusions and Future Work

Three fog cases have been modelled using the Met Office Unified Model vn5.3 at 12km horizontal grid resolution with 38 vertical levels and at 4km and 1km horizontal grid resolution with 76 vertical levels. These are 21 Feb 2003, 07 Nov 2003 and a pea-souper on 10 Dec 2003. The model forecasts have been verified both objectively and subjectively against the synoptic observations. Nimrod visibility analyses have also been used for comparison purposes.

For the case studies considered here, the model with 1km grid resolution appears to be qualitatively better than either of the other two models used, in that detailed forecast features due to the orography are much more clearly visible. The 1km model is also more consistent with the observations. However, it should also be noted that, in all three cases, the qualitative and quantitative differences between the 1km and 4km model forecasts are significantly less than the difference between either of these models and the 12km operational mesoscale forecast. In the 10 Dec 2003 case, the standard verification indicated that the 1km and 4km models performed markedly better in terms of visibility predictions than the 12km model, at least later on in the forecast period.

In the 21 Feb 2003 and 7 Nov 2003 cases, the 1km and 4km models both produce denser fog than the 12km model. In this respect the higher resolution models concur better with the observations.

The standard verification indicates that there is a consistent 0.5-1.0 degree bias in the screen temperature in the 1km and 4km models. A possible explanation is the increased vertical resolution in these models. However this still needs to be investigated and the actual cause has not yet been identified.

In each case, the 1km and 4km models both produce and dissipate the fog more quickly than the 12km model. For the 10 Dec 2003 case, it is particularly noticeable that there is a much greater degree of fog dissipation during the afternoon in the 1km and 4km models than in the 12km model. This is consistent with the observations for the case. In general, however, it has not been established whether the quicker response of the higher resolution models is more realistic. On some occasions the timing in the 12km model seems to be better, but as 12km is the operational resolution for which the model physics has been designed, this could just be a tuning effect.

In the 21 Feb 2003 case, the fog in the models is seen to spread with the synoptic flow to cover the south-east facing slopes of some of the hills in the domain. This effect is more pronounced in the higher resolution models in which the orography is more defined. However it has not been determined whether the spreading of the fog in this manner is realistic or not.

Although using a higher resolution model demonstrates some improvement, for example with respect to the orography, none of the model forecasts produced could yet be described as completely accurate. This is not surprising, given the complex nature of the fog forecasting problem.

As outlined above, the current verification also has limitations. It depends mainly on the synoptic observations, which may or may not be representative of the whole domain. Future research should make use of improved observational data, as and when this becomes available and practicable. This data will take two forms. Firstly, higher resolution research data is available or planned at specific sites – some of them airfields - which are prone to fog. However use of such data may necessitate extra effort in setting up the model for new domains, time for which needs to be adequately allocated in future research plans. Secondly, once high resolution fog products from Meteosat Second Generation become routinely available, these will be invaluable for verification purposes.

The main focus of future research needs to be on improving and optimising the model for fog forecasting at very high resolution. The model physics in the Met Office Unified Model, (the model upon which the local model we plan to develop will be based), has been designed to represent sub-grid scale processes for a broad range of model scales, from the current operational mesoscale resolution of 12km up to climate model resolutions of say 300km. Due to the general nature of the model, compromises and assumptions have to be made, which may not be appropriate for the very high model resolutions implemented in these case studies. Hence, the next stage of the project will critically assess aspects of the current model physics which strongly influence the fog formation - such as the radiation and microphysics schemes – and optimise their formulation for use at very high, i.e. 1km, resolution.

Acknowledgements

This work was funded by the Ministry of Defence Met Support Group as part of the ongoing “Development of Very High Resolution Models for Local Fog and Cloud Prediction” Project. This report was first issued as a milestone report for this project.

I would like to thank Humphrey Lean for his help in setting up and running the model and Peter Clark and Brian Golding for their guidance in the project and for useful comments on the manuscript.